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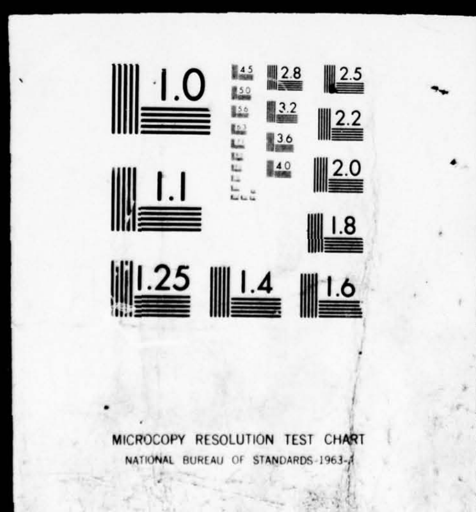

Report N00173-77-C-0184

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ANALYSIS OF SUPPLY SUPPORT IMPACTS ON EQUIPMENT OPERATIONAL AVAILABILITY

410 538

CACI, Inc.-Federal
Systems and Logistics Division
1815 North Fort Myer Drive
Arlington, Virginia 22209

December 1977

Final Report

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Prepared for:

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Naval Sea Systems Command (PMS-306)
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Research was conducted to determine the impact, on material condition of ships' system and equipments, of three parameters; reliability, maintainability, and supply response. A computer program was developed to facilitate the impact analysis. Also, a mathematical model was developed to generate a coordinated shipboard allowance list (COSAL) and, hence, reduce supply response time. The feasibility of using the computer programs was demonstrated. An investigation to determine data availability was conducted.

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EXECUTIVE SUMMARY

In his Objective #3, "Improvement of Material Condition of Ships in the Fleet," the Chief of Naval Operations established as a major, high priority goal the development of "a comprehensive program to promote an early improvement in the material condition of the fleet".

The Ship Support Improvement Project, administered by a Project Manager (PMS-306) within the Naval Sea Systems Command (NAVSEA), was specifically chartered to develop, in detail, those plans, procedures and management tools necessary for major advancement in Naval ship support capability, and, as a consequence, material condition.

Material condition of ships' systems, and equipments included within those systems, is considered to be a function of three factors; reliability, maintainability, and supply response. In order to apply resources to these factors on the basis of "maximum improvement in material condition for dollars expended," the following actions are required:

- Express, mathematically, the functional relationship between material condition of equipments and systems and reliability, maintainability, and supply response.

- Evaluate current values and feasible alternative values of reliability, maintainability, and supply response for systems, equipments and included components.

- Determine the time-dependent variable cost associated with current and alternative values of reliability, maintainability, and supply response.

- Provide a methodology for evaluating the impact, on material condition and cost, of variable levels of reliability, maintainability, and supply response.

- Evaluate the impact, on material condition and cost, of specific actions designed to improve one or more of the three components of material condition. Three examples are:

  - An engineering design change to improve reliability

  - Central requisitioning to reduce supply response time

  - Optimal allocation of spare items and repair parts stock to reduce supply response time

Research was conducted in the area of data evaluation, parametric analysis of material condition, and development and analysis of an optimal stock allocation model. This report describes the results of that research.

Material condition is expressed as operational availability, A_o. It is, essentially, a ratio of uptime to the sum of uptime and downtime. It is a function of

- Reliability - mean time between failure, MTBF

- Maintainability - mean time to repair, MTTR

- Supply response - mean supply response time, MSRT

Several sources of data were investigated and evaluated to determine the availability of information on equipment reliability, maintainability, and supply response. Specific equipment types were selected and a search for data on those equipments was conducted. (Actual equipment data was preferred to demonstrate the developed models and methodology.) The results of the data search are documented, and several conclusions and recommendations of a general nature are provided.

A computer program called ASUBO ANALYZER was developed for the express purpose of evaluating the impact, on operational availability, of varying values of MTBF, MTTR and MSRT. The program was exercised with data derived from the data

search phase of the analysis. Program descriptions and results of the analysis are included in the report.

The determination of feasible alternative values for reliability, maintainability, or supply response and the associated variable costs was not within the scope of the study. However, the ASUBO ANALYZER was modified to perform an economic analysis of trade-off between MSRT and MTTR. In order to demonstrate the feasibility of the methodology, cost functions were estimated and the program was exercised for selected equipments. The output reports show the minimum cost solution to the resource allocation problem.

Considerable effort was expended to develop a methodology for optimum allocation of repair parts stock to each of several locations in a supply/maintenance network based on the following criteria:

- For a given target value of operational availability, A_o, select and assign stock to the several locations at minimum cost, or

- For a given budget limitation, select and assign stock to the several locations such that A_o is maximized

The program is called the OPTIMAL A_o COSAL MODEL. It incorporates the following important features:

- A ship's Coordinated Shipboard Allowance List (COSAL) is developed based on the A_o criteria.

- Several equipment indentures may be considered.

- Several maintenance and supply echelons may be considered in the network.

- The model allows phase-in of equipment and multiple schedules.

- Optimizations may be "pure" at all locations; constrained by current policies or existing stock at some locations and optimized at remaining locations; or stock levels at some or all locations may be given and only the augmented stockage is by optimizations.

The OPTIMAL A_o COSAL MODEL was exercised for two equipment types, a seawater circulating pump and a computer. System stocks were calculated on the basis of current Uniform Inventory Control Point (UICP) policies. However, shipboard stocks were calculated by the optimal A_o COSAL methodology and by each of four other Navy policies for COSAL calculation. The results are provided in the report.

The major conclusions to be made from this research are as follows:

1. It is feasible to express operational availability, A_o, as a function of reliability, maintainability, and supply response.

2. The non-economic impacts of reliability, maintainability, and supply response on A_o are easily quantified if sufficient and reliable data is available.

3. It is feasible to determine the least cost allocation of resources to the three components of operational availability (reliability, maintainability, and supply response), again subject to the availability of reliable data.

4. The OPTIMAL A_o COSAL MODEL will generate a shipboard allowance list which is at least as cost effective as current Navy policies. In most cases, substantial cost savings, material readiness improvement, or both can be expected.

5. Although the feasibility of the developed methodology is demonstrated, considerable effort is required to obtain sufficient reliable data and to implement the schemes on a large scale.

It is recommended that:

1. There be continued research in the area of reliability, maintainability and supply response data acquisition, retention and update

2. An extensive effort be made to estimate the time-dependent variable costs associated with several levels of reliability, maintainability and supply response

3. There be continued research and development in optimal allocation of shipboard and system stock

4. Consideration be given to development of a plan to implement data acquisition procedures and the methodologies described herein

ACKNOWLEDGEMENTS

The success of a research effort of this type depends greatly on the enthusiastic and professional coorperation of others. In particular, the analysts who conducted the research and prepared this report are indebted to Mr. J. W. Prichard, Ship Support Improvement Project, Naval Sea Systems Command (PMS-306); Mr. J. C. Flynn, Mr. J. A. Gates, and Mr. B. L. Barrouck, Fleet Material Support Office; and Captain J. F. Blake, SC, USN and other officers of the staff of Commander, Surface Force Atlantic, Norfolk, VA.

CONTENTS

I. INTRODUCTION

Material condition of surface ships, their included systems, and equipments may be viewed as a function of three parameters: reliability, maintainability, and supply support. Operational availability, A_o, is used to express material condition. The three parameters are as follows:

- reliability - mean time between failure, MTBF
- maintainability - mean time to repair, MTTR
- supply support - mean supply response time, MSRT

The basic equation used to measure material condition is:

$$A_o = \frac{MTBF}{MTBF + MTTR + MSRT}$$

Given the above measure, research was conducted to determine the availability of data for equipment types, to determine the impact on A_o of alternative values of the three parameters, and to investigate an optimal methodology for developing a Coordinated Shipboard Allowance List (COSAL) and, hence, reduce MSRT.

Section II reports on the availability of data for the determination of equipment reliability and maintainability, and the calculation of MTTR given that the data is obtained. Section III discusses the information requirements and equations to determine MSRT and the availability of supply-related data.

A computer program called ASUBO ANALYZER was developed to facilitate a parametric analysis of A_o. The analysis methodology was demonstrated with data from two electronics equipments. Section IV describes the analysis. Also demonstrated is the feasibility of an economic analysis whereby a least cost allocation of resources to improvement in MSRT and MTTR is made.

Sections V, VI, and VII describe alternative methods of calculating a ship's allowance list of repair and spare parts. A new model, OPTIMAL A_o COSAL MODEL, was developed which will:

- for a given target value of A_o, select and assign stock to several locations at minimum cost, or
- for a given budget limitation, select and assign stock such that A_o is maximized.

This model was exercised with data on two equipments, a pump and a computer. The optimum methodology is compared with current Navy COSAL calculation methodology.

Section VIII provides conclusions and recommendations from each area of research. The three appendices describe programs and models used or related to the analyses.

II. DETERMINING BENCHMARK VALUES OF RELIABILITY AND MAINTAINABILITY

A. INTRODUCTION

The extent to which an equipment is operationally available is often taken as a measure of its reliability. However, a unit or system that was operational for six months and was down for repair for the next six months would, in the time span of a year, be deemed more reliable than a different unit or system that was operational only on alternate days during the year. Yet both equipments were operationally available for the same fraction of the year. Since all units of a given class of equipment are likely to experience different durations and frequencies of downtime, it is more meaningful to measure the reliability of that equipment in terms of the mean operational status of the class as a whole. For reasons elsewhere explained, the class level chosen in this study was the APL. The average operational experience of an APL appears to be best expressed as its mean time between failures (MTBF). Hence, one APL would be considered more reliable than another if its MTBF exceeded the MTBF of the second APL.

In the case of the two equipments cited above, the second can be brought back to operational status within a day. The other unit, however, needed six months for repair and obtaining parts. The former's maintainability is clearly superior despite the fact that its reliability is inferior to its counterpart. Several elements may combine to constitute the long continuous period of downtime experienced by the second equipment, namely administrative delay (paperwork, etc.), supply time (procurement of parts from POE, vendor, etc.), failure diagnosis, actual repair, and test time. The quality of reporting at present does not warrant an attempt to capture downtime data by these five constituent elements. Furthermore, the objectives of this study can be adequately realized by isolating only supply time and repair time. The latter is taken to include diagnosis and checkout, while supply and repair, between them, absorb administrative delay time involved.

The question of supply is discussed in Section III of this report. The present section addresses repair time which is equated to maintainability. When analyzing the repair experience of a group of APLs, it is more revealing if the mean time to repair (MTTR) of each is evaluated against some predetermined standard and/or compared with that of the other members of the group.

The problems of collecting the data needed for computing MTBF and MTTR are examined below. The equations derived are consistent with the logic used in the program ASUBO ANALYZER, described in Appendix A, and the parametric analysis conducted on two equipments and reported in Section IV.

B. MTBF DETERMINATION

MTBF is defined as the average length of time between consecutive failures for a given piece of equipment. When so defined, it is equivalent to uptime. In the CASREP (Casualty Reporting) system, it is the average time between a CASCOR (Casualty Correction) date and the next CASREP date for the same piece of equipment. In the 3-M (Maintenance Material Management) system, it is the mean time between a maintenance action closing, or its completion date, and the discovery date of the next failure for that equipment. 3-M reporting reflects equipment status as a result of the failure (operational, reduced capability, and non-operational). In this study, only failures resulting in non-operational status were regarded as relevant for MTBF computation.

The management concept underlying the CASREP and 3-M systems is exception reporting. Thus, uptime as such is not reported, but downtime is. Consequently, MTBF is more readily determined by collecting downtime data, uptime being the difference between total available time and downtime. On this basis, the following data elements are involved:

- The elapsed time, T, which is equivalent to the duration of the period studied

- The equipment population, i.e., the APL count, P, for that equipment, if installed in a U. S. active ship or activity.

- The total downtime, D, for all members of the population of a given APL. Thus,

$$D = \sum_{i=1}^{P} D_i$$

where D_i is the total downtime for E_i, the ith member of the APL's population. Downtime is disregarded if a failure only impairs but does not totally inhibit the operation of E_i. Severity codes C-2, C-3, and C-4 in the CASREP System would signal failures that meet this criterion for inclusion. Status code 2 in the 3-M System also qualifies. D_i, itself a summation is defined by:

$$D_i = \sum_{j=1}^{F_i} D_{ij}$$

where j is the j^{th} failure for equipment unit E_i. The summation extends over F_i, where F_i is the total number of non-operational failures for E_i.

- The total number of failures, F, resulting in non-operational status for the APL in question is the sum:

$$F = \sum_{i=1}^{P} F_i$$

Reliability of the equipment, represented by an APL, may be calculated by the following equation. The symbols MTBF and R are used for reliability.

$$\text{MTBF} = R = \frac{\text{(Population) x (Study Period) - (Total Downtime)}}{\text{(Total No. Failures)}} = \frac{PT-D}{F}$$

It is to be observed that the total number of failures, F, is not necessarily equal to a count of uptime intervals, U, in an analysis period. Therefore, mean time between failures calculated with U as the denominator might differ from that derived when F is used.

However, the discrepancy in the resulting value of MTBF, where it exists, tends to diminish as F increases. Since the ultimate objective is to measure A_o (operational availability), it is not significant whether F or U is used provided one is consistent in calculating all means. Such consistency, in effect, is equivalent to the cancellation of F (or U, if it is used) from the numerator and denominator of the A_o formula. For these reasons, we have chosen to compute and use F rather than U.

C. MTTR DETERMINATION

MTTR is defined as the average amount of time spent in maintenance actions aimed at correcting failures that reduce an equipment to a non-operational status. Three elements enter into the computation of the mean, namely the repair echelon, the probability that repair will be effected at that echelon, and the echelon's average repair time.

Four echelons have been identified as significant for the purpose of the present study. These are:

- On Ship repair (OS)
- On Ship repair with Technical Assistance (TA)
- Tender or Shipyard repair (TY)
- Overhaul or drydock (OH)

In order to compute the respective echelon probabilities and average repair times, the following data elements are required:

- The number of failures corrected by OS repair, N_1

- The number of failures corrected with TA, N_2

- The number of occasions requiring TY repair, N_3

- The number of times OH was performed on the APL in question, N_4

- The total number of relevant failures experienced by the APL, N, is given by:

$$N = \sum_{k=1}^{4} N_k$$

As is intended throughout this discussion, relevancy here implies degradation to a non-operational condition.

- The average time, L_1, required to complete an OS repair is given by:

$$L_1 = \frac{1}{N_1} \sum_{k=1}^{N_1} T_{1k}$$

where T_{1k} is the actual time required to repair the k^{th} failure corrected on ship by the ship's crew, similarly

- The average time, L_2, for a TA repair is:

$$L_2 = \frac{1}{N_2} \sum_{k=1}^{N_2} T_{2k}$$

- The average time, L_3, for a TY repair is:

$$L_3 = \frac{1}{N_3} \sum_{k=1}^{N_3} T_{3k}$$

- The average time, L_4, for an OH repair is:

$$L_4 = \frac{1}{N_4} \sum_{k=1}^{N_4} T_{4k}$$

The mean time to repair is a function of each echelon's repair time and the probability of repair at that level. The representative probabilities, Q, are derived from the following formulae:

- Probability, Q_1, of OS repair is:

$$Q_1 = N_1/N$$

- Probability, Q_2, of TA repair is:

$$Q_2 = N_2/(N-N_1)$$

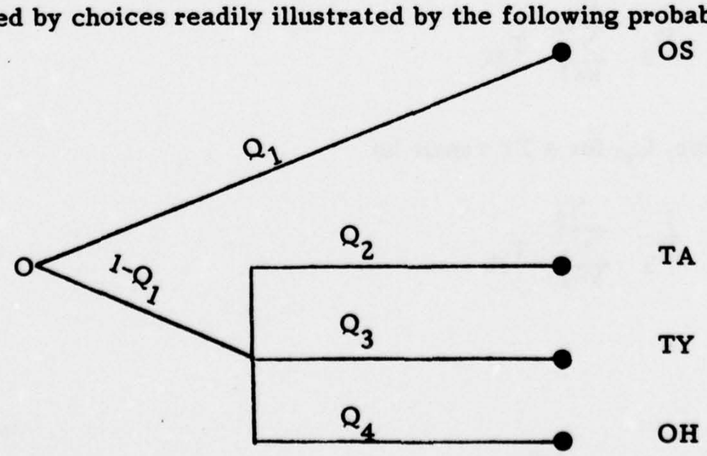
- Probability, Q_3, of TY repair is:

$$Q_3 = N_3/(N-N_1)$$

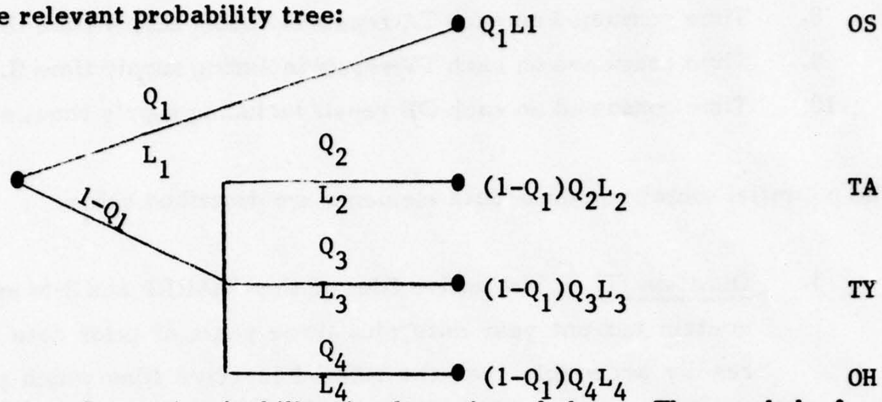
- Probability, Q_4, of OH repair is:

$$Q_4 = N_4/(N-N_1)$$

It is apparent that $Q_2 + Q_3 + Q_4 = 1.0$. This implies that the repair decision rules are governed by choices readily illustrated by the following probability tree:



In the A_o analyzer described in Appendix A, repair time for a TA, TY or OH correction includes the time consumed in obtaining parts, transportation, and administrative delay. Administrative delay may be caused by ship's scheduling, awaiting for ship to return to port or dispatching delay. With this understanding, the respective contributions of OS, TA, TY, and OH repair to MTTR is again evident from the relevant probability tree:



The resultant value for maintainability is then given below. The symbols for maintainability are MTTR or M.

$$MTTR = M = Q_1L_1 + (1-Q_1) \sum_{n=2}^{4} Q_n L_n$$

D. DATA REQUIREMENTS AND AVAILABILITY

The MTTR value for a given APL may be calculated from the above formula provided the basic data required for computation of Q and L are available. The following paragraphs discuss data availability.

Review of the elements involved in several equations above leads to the following data requirements:

1. Duration of study period (T)
2. APL population (P)
3. Number of OS repairs (N_1)
4. Number of TA repairs (N_2)

5. Number of TY repairs (N_3)
6. Number of OH repairs (N_4)
7. Time consumed on each OS repair excluding supply time (L_1)
8. Time consumed on each TA repair including supply time (L_2)
9. Time consumed on each TY repair including supply time (L_3)
10. Time consumed on each OH repair including supply time, etc. (L_4)

The potential sources of these data elements are described below:

1. Duration (T) - The active files of the CASREP and 3-M systems always contain current year data plus three years of prior data and are more readily accessible than the related inactive files which predate them. Since they cover a reasonable time span, they are suitable for A_o study with respect to those data elements which they maintain.

2. Population(P) - The current APL population may be obtained from the Weapons System File. However, it is not possible to extract population statistics for prior dates. Thus, if the study period, T, covers the time span of active CASREP or 3-M data, one is constrained to assume that the current population is a valid statistic for each year of the study. If this assumption is invalid, MTBF will be overstated or understated as follows:

   - For a population increase in the period, MTBF will be too high.
   - For a population decrease in the period, MTBF will be too low.

3. OS Repairs (N_1) - Type Availability code 4 in the 3-M system indicates that the ship's force can correct the failure. Element GOLF-A in a CASREP message states NONE when the repair is to be effected without outside help. In the CASREP coding section, this message is coded S to indicate repair by ship's force. A count of the relevant failure records which carry these codes in either system (whichever is chosen for study) will give N_1.

4. TA Repairs (N_2) - Type Availability code 3 in Failure records of the 3-M master file is the key to developing an N_2 count of TA repairs. In the CASREP system, the relevant code is T.

5. TY Repairs (N_3) - In 3-M, Type Availability code 1 indicates shipyard (or ship repair facility), while code 2 indicates IMA, that is, tender or repair ship intervention. A count of Failure records with codes 1 and 2 gives N_3. In the CASREP system, records with Type Availability code R would be included in the N_3 count.

6. OH Repairs (N_4) - Code 0 indicates overhaul and code D indicates drydock repair in the CASREP system. 3-M does not provide for coding OH repair in either of the two fields that might be possible sources for this data element, namely, the Type Availability field or the Screening field. The total of code O and code D records gives N_4 when CASREP Failures are the subject of A_o study.

7. OS Repair Time (L_1) - When CASREP parts are received, the ship reports "hours awaiting parts" to the CASREP system. The latter accepts the information as a ZZ transaction and converts the hours to non-operational downtime days related to supply (NORS). When the failure is finally corrected, a CASCOR is submitted. The elapsed time between the CASCOR date time group (DTG) and the DTG on the CASREP equals the total downtime. If the NORS downtime is subtracted from this figure, the difference is the actual time spent on the OS repair. In the text above, we referred to this value as L_1. Thus:

$$L_1 = \text{(CASCOR DTG - CASREP DTG) - NORS Days}$$

It is to be understood that the computation herein described applies only to those CASREP records which carry a Type Availability code S or T.

In the 3-M system, the number of days between the Closing Completion Date and the Date of Issue of the last part issued gives the closest possible approximation to the repair time. The figure is inaccurate to the extent that supply transportation time is included in repair time.

This computation is applicable only to 3-M records with Type Availability code 4 or 3.

8. TA Repair Time (L_2) - The computation of L_2 is identical to that described for L_1. (Type Availability codes S or T are applicable).

9. TY Repair Time (L_3) - The model described in Appendix A does not attempt to distinguish between supply time and actual repair time in the case of TY REPAIR ACTIONS. Thus, L_3 is equal to total downtime in such instances. In the CASREP system, the elapsed time between the CASCOR DTG and the CASREP DTG is to be taken as equal to L_3, if the Type Availability code is R.

   In 3-M, the elapsed time between the Closing Completion Date and the Failure Date of Discovery may be equated to L_3 when the Type Availability code is 1 or 2.

10. OH Repair Time (L_4) - Using CASREP data, L_4 is computed exactly like L_3. The qualifying Availability code is O or D. 3-M does not provide information that would permit identification of OH repair time.

E. CONCLUSIONS AND RECOMMENDATIONS

If an A_o study is undertaken using CASREP data, all of the ten elements required for computation of reliability and maintainability could be extracted, theoretically, from the CASREP system. However, only APL failures that significantly degraded mission capability as defined by severity codes C-2, C-3, and C-4 would be available for analysis. 3-M covers a broader spectrum of maintenance actions in that it provides for the reporting of all repairs except those performed in drydock or overhaul. In the light of these limitations, therefore, the following observations are afforded by way of qualifying any A_o conclusions that might be drawn from a study of CASREP or 3-M data.

Our experience in data extraction for a selected set of eight APLs, five relating to a UNIVAC computer NHA-AN/UYK-7(V), and three as components of a Davidson pump, was as follows:

- The pump APLs did not exist in the 3-M data bank and no CASREPS were reported against them during the study period, January 1974 to October 1977.

- Of the other five computer-related APLs, two had one CASREP each during the same period. 15 non-operational failures were reported in the 3-M system. In addition, 11 failures were reported in which the equipment status was stated as 'Reduced Capability'. For 23 other maintenance actions, the status was shown as 'Operational'. These 34 failures were not included in our A_o analysis, though it would appear a decision would be required from higher authority regarding the treatment (exclusion or inclusion by factoring) of reduced capability failures in any subsequent extension of this initial A_o study.

- 13 records pertaining to three of the five selected APLs in the 3-M data bank contained parts data only. This means that parts issue transactions entered the 3-M system to create maintenance records, yet the failures themselves were never reported. Such records are useless for A_o analysis purposes but their presence indicates that A_o is probably lower in value than that determined solely on reported failures.

- Inconsistency exists in the processing of CASREPS which are not CASCORed just prior to a ship's overhaul. Two practices appear to be common:

    - The CASREP may be cancelled, the required repair being done during overhaul with the maintenance action not reported. As a consequence, the CASREP system does not reflect the downtime in its statistics.

- The CASREP may be left open and a CASCOR submitted when the necessary corrective action is completed during overhaul. In this case, the downtime and repair time are reflected in CASREP reports.

- All overhaul repairs should be reported into the 3-M system.

- In the context of A_o analysis, population statistics would be improved if it were possible to determine the birth date of each member of all APL groups. This would permit more accurate computation of APL total elapsed time and, consequently, MTBF.

- The exclusion of 'Reduced Capability' failures from A_o study probably has less impact on accuracy than has the apparently low quality of 3-M reporting. The latter should be addressed before the former is considered.

- Personnel CASREPs are not related to APLs and are to be omitted in A_o evaluations.

III. MEASUREMENT OF ELEMENTS OF SUPPLY RESPONSE TIME

A. INTRODUCTION

The CASREP system recognizes two supply intervals defined as mean requisition submission and processing time (MRSPT) and mean requisition response time (MRRT). The latter includes parts shipment time. The former does not. The CASREP's DTG is considered the starting point of the action. Any delay in a requisition's preparation and its receipt at the designated supply point is outside supply control, yet such delay is charged to the supply function, as is parts distribution time.

When a ship submits a CASCOR, its hours awaiting parts are stated, thereby permitting computer computation of supply time. In 3-M, the issue date of each part is reported. The issue date of the last part, when subtracted from the discovery date, gives the supply interval for that particular failure.

Each APL failure will experience a different supply time, which is seen to be a function of three factors.

- The probability, P, that parts are needed for the repair in question.
- The probability, B, that a requisition placed on a given supply point can be satisfied by that supply point.
- The time, T, it takes a supply point to get the material into the hands of the mechanic.

Because of such variability in response time it is necessary to devise a method for measuring the mean supply response time (MSRT). The resultant value for a given APL is then used in computing A_o for that APL.

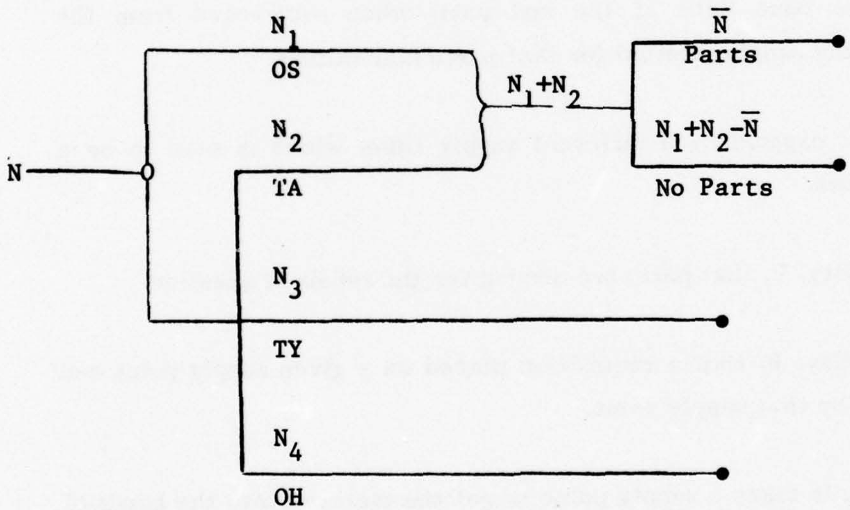
The assumptions and equations discussed below are consistent with those used in the ASUBO ANALYZER, described in Appendix A, and the parametric analysis conducted on two equipments and reported in Section IV.

B. MSRT DETERMINATION

The three factors that influence supply time must be identified more precisely before MSRT can be computed.

Since supply time is not being distinguished from repair time in the case of TY and OH repairs, the probability that parts are needed relates only to repairs effected on the ship; that is, at echelon OS or TA.

If $\bar{N}$ is the number of casualties repaired on board that needed parts, then the parts probability factor, P, is obtained from the following tree:



$$P = \frac{\bar{N}}{N_1+N_2}$$

All Ns refer to repair action counts.

Five supply echelons have been identified for A_o purposes:

- Ship's Store, SS
- Mobile Logistic Supply Force, AFS

- Stock Point, POE, – Norfolk, Oakland, etc.
- Wholesale System, ICP
- Vendor, V

For each echelon, i, the mean supply time, T_i, and the probability, B_i, of satisfying demand are required. The supply logic incorporated into the A_o analyzer is based on the assumption that, if a parts requisition cannot be satisfied at the SS level, it is referred to the AFS. If the AFS fails, the requisition passes to the ICP. In the final analysis, the demand is placed with the vendor who is presumed to be capable of fulfilling it. This means that vendor supply probability is 1.

The following data elements are required by the MSRT formula:

- The number ($\bar{N}$) of OS and TA repairs that required parts

$$\bar{N} = \sum_{p=1}^{5} N'_p$$

where each N'_p is defined below.

- The number of casualties (N'_1) for which parts were supplied by the SS; this leads to the probability (B_1) of supply at the SS echelon

$$B_1 = \frac{N'_1}{\bar{N}}$$

- The number of casualties (N'_2) for which parts were supplied by an AFS; used in calculating the probability (B_2) of AFS supply

$$B_2 = \frac{N'_2}{\bar{N} - N'_1}$$

- The number of casualties (N'_3) for which parts were supplied by a POE, which leads to the probability (B_3) of POE supply

$$B_3 = \frac{N'_3}{\bar{N} - N'_1 - N'_2}$$

- The number of casualties (N'_4) for which parts were obtained through the ICP, from which the ICP supply probability (B_4) is given by

$$B_4 = \frac{N'_4}{\bar{N} - N'_1 - N'_2 - N'_3}$$

- The number of casualties (N'_5) for which the vendor supplied parts

$$B_5 = \frac{N'_5}{\bar{N} - N'_1 - N'_2 - N'_3 - N'_4}$$

$$= \frac{N'_5}{N'_5} = 1$$

- The average time (T_1) required to obtain parts from the SS, a value given by the formula

$$T_1 = \frac{1}{N'_1} \sum_{g=1}^{N'_1} T'_q$$

- where T'_q is the actual time required to obtain those parts from Ship's Stock that are needed to repair the q^{th} casualty.

- The average time (T_2) required to obtain parts from an AFS

$$T_2 = \frac{1}{N'_2} \sum_{r=1}^{N'_2} T'_r$$

- The average time (T_3) required to obtain parts from a POE

$$T_3 = \frac{1}{N'_3} \sum_{s=1}^{N'_3} T'_s$$

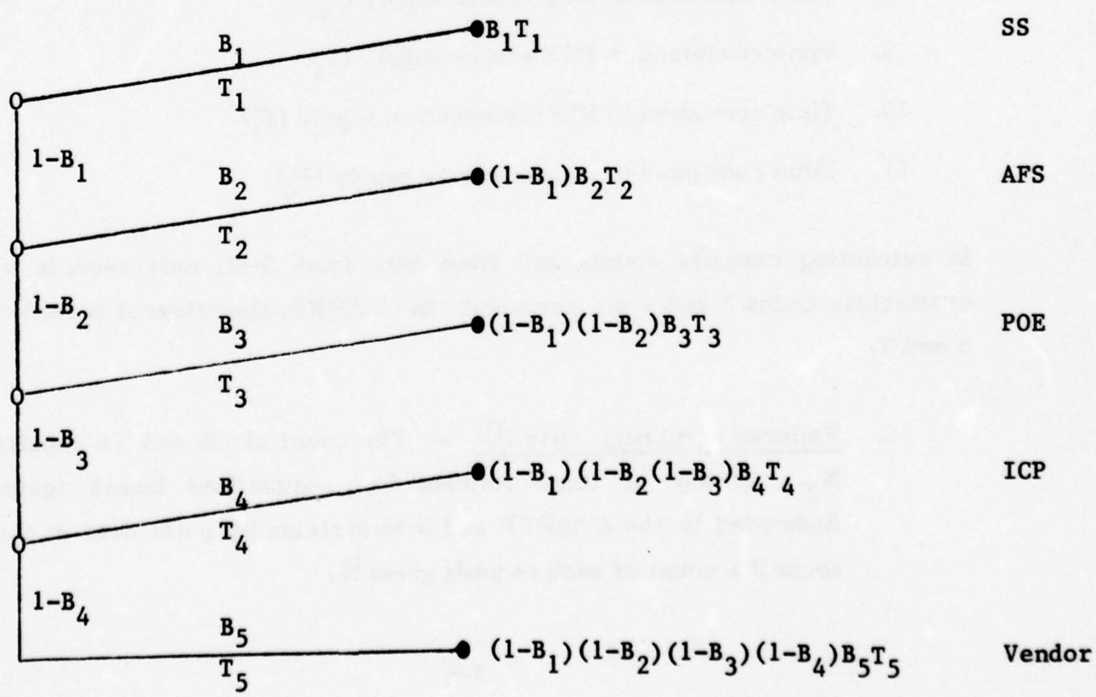
- The average time (T_4) required to obtain parts through the ICP

$$T_4 = \frac{1}{N'_4} \sum_{t=1}^{N'_4} T'_t$$

- The average time (T_5) required to obtain parts from a vendor

$$T_5 = \frac{1}{N'_5} \sum_{u=1}^{N'_5} T'_u$$

The mean time to satisfy the parts needs for a repair conducted on ship (OS or TA) is a function of the probability of supply from the various supply echelons and the average time to respond to a requisition placed on these echelons. The time contribution to MSRT by each echelon is seen from the following supply probability tree:



The resultant value(s) is the sum of the five supply source contributions:

$$\text{MSRT} = S = B_1T_1 + \sum_{v=1}^{4} (1-B_1)\ldots(1-B_v)\, B_{v+1}T_{v+1}$$

C. DATA REQUIREMENTS AND AVAILABILITY

The requirements for and the availability of failure count data and echelon supply times are discussed in the following paragraphs.

The list of required data elements for MSRT computation follows:

1. Number of OS and TA repairs requiring parts ($\overline{N}$)
2. Number of SS supplied casualties (N'_1)
3. Number of AFS supplied casualties (N'_2)
4. Number of POE supplied casualties (N'_3)
5. Number of ICP supply interventions (N'_4)
6. Number of vendor supplied casualties (N'_5)
7. Time consumed in SS source supply (T'_q)
8. Time consumed in AFS source supply (T'_r)
9. Time consumed in POE source supply (T'_s)
10. Time consumed in ICP intervention supply (T'_t)
11. Time consumed in vendor source supply (T'_u)

In extracting casualty counts and time data from 3-M, only records with type availability codes 3 and 4 are pertinent. In CASREP, the relevant record codes are S and T.

1. <u>Failures Requiring Parts ($\overline{N}$)</u> – The count of OS and TA repairs is N_1 + N_2. If any of these failures had requisitions issued against them (indicated in the CASREP and 3-M systems by parts data in the failure record) a count of such records gives $\overline{N}$.

2. SS Supply Count (N'_1) – Parts drawn from store will be indicated in 3-M by the Mechanic's Closing Comments, but the action is not "coded." CASREP indicates if each part was on the Allowance List and also on board. A count of such failure records gives N'_1.

3. AFS Supply Count (N'_2) – AFS as a supply source is not reported in 3-M or the CASREP system, hence the count N'_2 is not available.

4. POE Supply Count (N'_3) – Neither 3-M nor CASREP provides data for determining N'_3.

5. ICP Supply Count (N'_4) – This count is not directly available from 3-M or CASREP.

6. Vendor Supply Count (N'_5) – This count is not available in the 3-M and CASREP systems.

7. SS Supply Time (T'_q) – In CASREP, the Hours Awaiting Parts is given. This permits computation of a Parts Receipts Date which, when subtracted from the CASREP DTG, gives T'_q in days.

Since N'_2, N'_3, N'_4, and N'_5 actions cannot be identified, it is not possible to isolate T'_r, T'_s, T'_t or T'_u in either the 3-M or CASREP systems.

D. CONCLUSIONS AND RECOMMENDATIONS

The failure to identify the supply source in CASREP and 3-M reporting precludes direct calculation of MSRT. The following comments suggest how this deficiency might be corrected or, at least, partially overcome.

- Requiring the mechanic to code and report the supply source in the CASCOR would provide the necessary identification data. A programming change would be needed, of course, to reflect the new information in the master file and, eventually, in Report Symbol Sup 4400.28-6 and similar reports.

- A SITREP is often submitted when parts are received and installed. Coding of the supply source might be made mandatory.

- In the Closing Action in the 3-M system, the mechanic usually states "MA Completed, Parts Drawn from Supply " By also coding the source, e.g., SS = 1, AFS = 2, POE = 3, ICP = 4, Vendor = 5, No. Parts = 0, he would facilitate the kind of source analysis essential to MSRT computation. It is recognized that this may be an excessive administrative burden for the mechanic.

- It would be possible to analyze SPCC supply data, either through manual review of requisitions or by special programming that would permit retrieval from the Supply Master File, to determine MSRT and supply probabilities by COG. The values thus determined could then be applied to APLs on the basis of the cog, if any, in each APL. The contribution of each cog would be recognized by appropriate weighting factors. This concept was explored in the Ship's Supply Study (S_4) sponnsored by Materiel Division (OP41), Office of CNO.

- In the CASREP system, a Transaction History File is updated daily. Certain records contain Hold/Status Activity and Status/Shipment Activity data. In theory, it would be possible to pass this tape file and extract supply point information for determination of the probability (B) and the time (T) of requisition response for each of the five designated supply echelons. The limitations to current exploitation of this potential information source are:

  - Programs do not exist for extracting the required data, interpreting the status codes, and computing B and T.

  - If the programs did exist, the file search time might be considerable because of the large volume of records to be scrutinized.

  - SS and AFS supply status information is not routinely submitted to this file; more diligent reporting is necessary for the approach to become viable.

- The MILSTEP system contains supply and transportation data that are relevant to A_o analysis. At present, however, it is not a satisfactory vehicle for research because:

  - At any time, it contains only six months of data. A retained summary file containing relevant data for the preceding six months would be helpful.

  - Retrieval programs do not exist for extracting selected information from the file.

  - It identifies POE and ICP supply, but not SS, AFS or Vendor.

  - It tracks supply time from receipt of a requisition at a supply point until the material is delivered at a POD; the full supply interval is not covered.

- In the 3-M system, we observed that many parts issued dates were subsequent to the related failure closing action dates. Such occurrences reduce the reliability of 3-M as a source of supply information.

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IV. A_o PARAMETRIC ANALYSIS

A. INTRODUCTION

Military logistics planners need a method for measuring the effectiveness of weapon systems and included equipments, and for relating that measure to equipment reliability, maintainability and supply response time. With such a measure and sufficient data support they can make appropriate decisions regarding the assignment of resources to improvements in equipment reliability, equipment maintainability, and supply response

The purpose of this section is to demonstrate a methodology which logisticians may use to make cost-effective resource allocation decisions. Two electronic equipments are used for demonstration purposes,one with high reliability and the other with low reliability. The emphasis, however, is not on the actual results of the calculations, but on the methodology itself and its ease of application. The point to be made is this:

> With sufficient data on reliability, maintainability, supply response, and associated costs functions, it is practical to determine an optimum allocation of dollars to reliability, maintainability, and supply response to achieve a specified level of material readiness.

Operational availability, A_o, is the measure of effectiveness selected for this analysis. It is a function of the three parameters: reliability, maintainability, and supply response time. A methodology is provided whereby the impact on A_o of improvements to the three parameters may be evaluated. With the methodology, logistics planners may determine, for example, that a one-day improvement in supply response will increase A_o more than a one-day improvement in maintainability or reliability.

For a complete analysis, however, data on the cost of reliability, maintainability, and supply response as a function of time is required. No cost data was collected in this effort. However, a complete cost analysis methodology and demonstration is a logical and necessary extension of this work.

To illustrate how this may be done, maintainability and supply response cost functions were assumed and an analysis of the trade-off between the two parameters was conducted. A least cost solution is obtained for selected values of operational availability. The methodology may be extended to optimization over all three parameters.

B. NON-ECONOMIC PARAMETRIC ANALYSIS

Equipment operational availability, A_o, as defined herein, is a function of reliability, maintainability, and supply response time. Specifically:

$$A_o = R/(R + M + Q_1 PS)$$

where,

- R = equipment reliability expressed as mean time between failure (MTBF) or mean time between corrective maintenance action (MTBCMA), in days.
- M = equipment maintainability expressed as mean time to repair (MTTR), in days. This is an average, or expected value, over the several echelons where the equipment may be repaired. If the repair is off ship, this time includes time in transportation and awaiting parts and personnel.
- S = mean supply response time (MSRT), in days. This is the average, or expected value, over the several echelons which may supply equipment-related parts to the ship in support of the ship's maintenance actions on the equipment.
- Q_1 = probability that the repair to the equipment will be done on the ship by the ship's crew.
- P = probability that the repair action requires one or more parts.

A computer program called ASUBO ANALYZER was developed for the express purpose of calculating initial values of the above parameters for one or more equipments. Also, the program allows reliability, maintainability, and supply response to vary to determine the impact that changes in these quantities have on A_o. Appendix A provides a mathematical description of the program, a co plete list of input data elements and examples of output reports.

The purpose of the A_o parametric analysis is to evaluate a methodology for measuring the impact on A_o caused by varying MSRT and to evaluate this impact relative to the impact of changes to other parameters.

As previously mentioned, two electronics equipments were used for the analysis. The original intention, however was to use one electronics equipment, a computer, and one HM&E equipment, a pump. The active Navy population of these equipments, by Allowance Parts List (APL) is as follows:

	Population
• Seawater Circulation Pump	
APL 016120501E Centrifugal Pump	2
APL 174753829, AC Motor	2
APL 151209978, Starter Motor	2
• AN/UYK-7(V) Computer	
APL 61399858, Controller Unit	73
APL 62982331, Electric Cabinet	83
APL 79738784, Power Supply	90
APL 92233919, Test Set, Computer Logic	189
APL 62405281, Central Processor	50

An attempt was made to obtain sufficient data on these equipments to conduct a parametric analysis. The paucity of data precluded the use of these equipments for the analysis. In particular:

- The CASREP data bank included only one report for each item of equipment over a period of nearly four years, January 1974 through October 1977.
- The 3-M data bank included no information on the pump over the same period of three years and ten months.
- Thirteen actions were noted in the 3-M data bank for the computer. The data was not considered to be reliable since all parts receipts were recorded after completion of repair and parts were issued against job control numbers in cases where the repair action itself was not reported.

In view of the difficulties encountered in attempting to obtain data for the two selected equipments, data on two electronic equipments was used for the analysis. The two equipments are:

- AN/USM-117C Oscilloscope
- AN/WLR-1C Receiving Set

They were chosen because of data availability and the difference in reliability.

Reliability, maintainability, and supply response data for these two equipments was obtained from a recent study by the Center for Naval Analyses (1) which, in turn, derived the data from the 3-M system and the "S-4" study (2). Table 4-1 lists the input data for each equipment. Maintainability and supply response data was aggregated, in reference (1), by cognizant inventory control point. Both equipments include parts which are primarily "9N" cog, hence the data similarity. The parts lists for the two equipments were scanned to determine the predominant cog associated with the included parts. Supply response time and supply availability are a function of the cog. In practice, the supply response time for a given maintenance action for an equipment is equal tothe time required to receive the last part required. For example, if k parts were required during a given maintenance action and X, X_2 . . . X_k were the response times to receive parts 1, 2, 3, . . ., k respectively, the supply response time would be equal to X_k assuming all parts were ordered at the same time. The solution to this problem is addressed in reference (2). Since the examples in this report are for demonstrating the ASUBO Analyzer, no attempt was made at applying the solution contained in reference (2) or developing the data required by that solution.

Table 4-2 lists the initial values of reliability, maintainability, and supply response and operational availability calculated by model. Equations (2), (3) and (4), Appendix A, were used for the calculations. The Center for Naval Analyses values of mean delay time, MDT (which is the sum of maintainability, supply response and administrative delay), and A_o are listed for each equipment. These were not used in the analysis since information on maintainability and supply response time are needed for demonstration of the methodology.

The first step in the parametric analysis is to vary each of the three parameters (reliability, maintainability, and supply response) independently to determine the impact on A_o. Figures 4-1 through 4-6 demonstrate these impacts graphically. Note, specifically, the following:

- The oscilloscope is very reliable, MTBCMA = 4838 days, and increased reliability does little to improve A_o. See Figure 4-1.
- The receiver set A_o is improved from .887 to .95 with an increase in reliability of about 100%. See Figure 4-2.

- Due to the oscilloscope's high reliability, it will tolerate a large increase in MTTR and MSRT and still maintain an A_o in excess of .98. Figures 4-3 and 4-5.

- The receiver set will not tolerate large increases in MTTR and MSRT. An MTTR of about 50 days and an MSRT of about 40 days will drop the A_o to about .8. Figures 4-4 and 4-6.

Figures 4-7 and 4-8 show graphically the impact of improvement, or degradation, in reliability, supply response, and maintainability. An improvement is positive if reliability is increased and if maintainability or supply response time is reduced. Note the following:

- The oscilloscope initial values show a high reliability and high A_o, .994. The impact of a forty-day improvement or degradation in reliability has little impact on A_o. The reliability of the receiver set is much less. The initial A_o value of .887 may be improved slightly by increasing reliability.

- The impacts of improvement or degradation in maintainability and supply response are nearly identical. This is due to the high probability of shipboard repair, .9, and the high probability that parts are required for each repair action, .95.

- The impacts of improvement or degradation in maintainability and supply response are significantly greater than for changes to reliability. In other words, if the cost of improving a day's worth of reliability is greater than or equal to the cost of improving maintainability or supply response, then the emphasis should be on improvement of maintainability or supply response. The choice between improving maintainability or supply response may be made on a cost basis.

- There are limits to the level of A_o which may be achieved by improving

maintainability and not improving supply response. And, of course, there is an A_o limit for improving only supply response time. These limits are:

	A_o Limit for Improvement in:	
	Maintainability	Supply Response
AN/USM-117C Oscilloscope	.9986	.9955
AN/WLR-1C Receiving Set	.9830	.9120

- The impacts of maintainability and supply response improvements are much greater for the receiver set than for the oscilloscope.

The parametric analysis is continued with the determination of the values of three partial derivatives as a function of reliability, maintainability, and supply response. The three derivatives are:

- $\delta A_o/\delta R$ – A measure of the rate of change in A_o with respect to reliability.

- $\delta A_o/\delta M$ – A measure of the rate of change in A_o with respect to maintainability.

- $\delta A_o/\delta S$ – A measure of the rate of change in A_o with respect to supply response time.

For each of the two equipments the three derivatives were calculated for varying values of reliability, maintainability, and supply response time. Figures 4-9 through 4-26 are plots of the resulting functions.

Figures 4-9 and 4-10 demonstrate the impact of reliability on the partial derivative $\delta A_o/\delta R$. As reliability is decreased below the initial value, the impact of reliability changes on A_o is increased. Above the initial value there is little impact, as can be seen by the long, flat tail in each figure.

Figures 4-11 and 4-12 show the impact of maintainability on the partial derivative $\delta A_o/\delta R$. As maintainability is increased, the impact of reliability changes on A_o are

increased. It is apparent from Figure 4-12 that this impact decreases as MTTR is increased. The function appears as a straight line in Figure 4-11 due to the high reliability of the oscilloscope. Note that the left portion of the function in Figure 4-12 also appears to be a straight line.

Figures 4-13 and 4-14 may be interpreted exactly as the two previous figures. Supply response is varied rather than maintainability.

Figures 4-15 and 4-16 are plots of $-\delta A_o/\delta M$ as a function of reliability. Comparison with Figures 4-9 and 4-10 shows that, at all levels of reliability, A_o is more responsive to changes in maintainability than to changes in reliability. However, as in Figures 4-9 and 4-10, the impact weakens as reliability is increased.

Figures 4-17 and 4-18 are plots of $-\delta A_o/\delta M$ as a function of maintainability. Note the difference in slope between these functions and those in Figures 4-11 and 4-12. The absolute value of $\delta A/\delta M$ decreases with increased maintainability, but the absolute value of $\delta A/\delta R$ increases. The impact on A_o of changes in maintainability is considerably greater than the impact on A_o of changes in reliability, at all levels of maintainability. A similar analysis may be made by comparing the functions in Figures 4-19 and 4-20 with those in Figures 4-13 and 4-14.

Figures 4-21 through 4-26 show $-\delta A_o/\delta S$ as functions of reliability, maintainability, and supply response. These functions are similar to those in Figures 4-15 through 4-20, and their analysis parallels the analysis of functions in Figures 4-15 through 4-20. Note, however, that the impact on A_o of changes in supply response are slightly less than the impact on A_o of changes in maintainability at all levels of reliability, supply response, and maintainability.

Calculations and plots for the above analysis are provided easily and quickly by the ASUBO ANALYZER. Many equipments may be subjected to the analysis in one run of the program. Switches are included to allow the user to suppress related reports and graphs. Appendix A documents the program.

C. ECONOMIC ANALYSIS

A comprehensive analysis of trade-offs among reliability, maintainability, and supply response is required in order to approach optimum resource allocation decisions. However, in recognition of the essentiality of this phase of the analysis, cost functions were estimated and the ASUBO ANALYZER was modified to provide a trade-off analysis between supply response and maintainability. The hyperbola function was chosen to represent the cost/time relationship. This is a continuous function and is well suited to the demonstration. In reality, however, the cost functions would probably be sets of points (cost, time) representing feasible alternatives for maintainability, reliability, and supply response. The cost functions used were derived from the following assumptions:

	Supply Response	Maintainability
Current time dependent variable cost	$ 3,420	$6,000
Ratio: Alternative time/current time	.4	.5
Variable cost for alternative time	$10,260	$9,600
Minimum cost, regardless of time	$ 2,565	$4,800

Figure 4-27 demonstrates the results of an economic analysis of the trade-off between maintainability (MTTR) and supply response (MSRT). For each of several values of A_o and MTTR,the cost of MSRT + MTTR is provided. (A value of "999999" indicates either excessive cost or a non-attainable value of MTTR or MSRT.) Also, for each value of A_o, the minimum cost is given and the values of MSRT and MTTR required to achieve this minimum. Note that as the A_o requirement decreases, the minimum cost approaches $7365, the sum of $2565 and $4800. Also, note that for A_o of .5 or less, the minimum MTTR value is greater than the 130.93 days, which is 6.0 times the initial value of MTTR calculated by the programs.

The economic analysis of Figure 4-27 was based on the reliability, maintainability, and supply response values calculated for the AN/WLR-1C receiver set. The results are shown for demonstration purposes, however, since the cost functions were estimated and are not based on knowledge of the cost of reliability, maintainability, and supply response associated with the receiver set.

TABLE 4-1. INPUT DATA FOR TWO ELECTRONICS EQUIPMENTS

INPUT DATA FOR EQUIPMENT 1: AN/USM-117C OSCILLOSCOPE

MEAN TIME BETWEEN CORRECTIVE MAINTENANCE ACTIONS (UNADJUSTED) 4838 DAYS

OPERATING FACTOR 1.00 PROBABILITY THAT PARTS ARE REQUIRED .95

PROBABILITY OF REPAIR		TIME TO REPAIR	
AT SHIP	.90	AT SHIP	15.00 DAYS
BY TECH ASSIST	.35	BY TECH ASSIST	90.00 DAYS
AT YARD OR TENDER	.62	AT YARD OR TENDER	76 DAYS
IN OVHL OR DRYDOCK	.03	IN OVHL OR DRYDOCK	153 DAYS

PROBABILITY OF SUPPLY AVAILABILITY		TIME TO SUPPLY THE SHIP	
BY SHIP	.59	BY SHIP	.13 DAYS
BY MOBILE LOGISTIC FORCE SHIP (AFS)	.55	BY MOBILE LOGISTIC FORCE SHIP (AFS)	8.0 DAYS
BY POINT OF ENTRY (STOCK POINT)	.64	BY POINT OF ENTRY (STOCK POINT)	31.4 DAYS
BY WHOLESALE SYSTEM (ICP)	.93	BY WHOLESALE SYSTEM (ICP)	35 DAYS
BY VENDOR	1.00	BY VENDOR	84 DAYS

DATA ADJUSTMENT FACTOR, MAINTENANCE 1.00
DATA ADJUSTMENT FACTOR, SUPPLY 1.00

INPUT DATA FOR EQUIPMENT 4: AN/WLR-1C RECIEVING SET

MEAN TIME BETWEEN CORRECTIVE MAINTENANCE ACTIONS (UNADJUSTED) 226 DAYS

OPERATING FACTOR 1.00 PROBABILITY THAT PARTS ARE REQUIRED .95

PROBABILITY OF REPAIR		TIME TO REPAIR	
AT SHIP	.90	AT SHIP	15.00 DAYS
BY TECH ASSIST	.35	BY TECH ASSIST	90.00 DAYS
AT YARD OR TENDER	.62	AT YARD OR TENDER	76 DAYS
IN OVHL OR DRYDOCK	.03	IN OVHL OR DRYDOCK	153 DAYS

PROBABILITY OF SUPPLY AVAILABILITY		TIME TO SUPPLY THE SHIP	
BY SHIP	.59	BY SHIP	.13 DAYS
BY MOBILE LOGISTIC FORCE SHIP (AFS)	.55	BY MOBILE LOGISTIC FORCE SHIP (AFS)	8.0 DAYS
BY POINT OF ENTRY (STOCK POINT)	.64	BY POINT OF ENTRY (STOCK POINT)	31.4 DAYS
BY WHOLESALE SYSTEM (ICP)	.93	BY WHOLESALE SYSTEM (ICP)	35 DAYS
BY VENDOR	1.00	BY VENDOR	84 DAYS

DATA ADJUSTMENT FACTOR, MAINTENANCE 1.00
DATA ADJUSTMENT FACTOR, SUPPLY 1.00

TABLE 4-2. INITIAL VALUES; RELIABILITY, MAINTAINABILITY, SUPPLY RESPONSE

	Equipment 1 AN/USM-117C Oscilloscope	Equipment 2 AN/WLR-1C Receiving Set
Reliability (MTBCMA), days	4838	226
Maintainability (MTTR), days	21.82	21.82
Supply Response (MSRT), days	8.14	8.14
Operational Availability, A_o	.994	.887
*Mean Delay Time (MDT), A_o	98	56
*A_o with MDT values	.98	.81

*Calculated by a Center for Naval Analyses study but not used since a breakout of delay attributed to repair or supply is required for demonstration of the methodology. Also, MDT, Mean Delay Time, includes maintainability, supply response time, and administrative delay time.

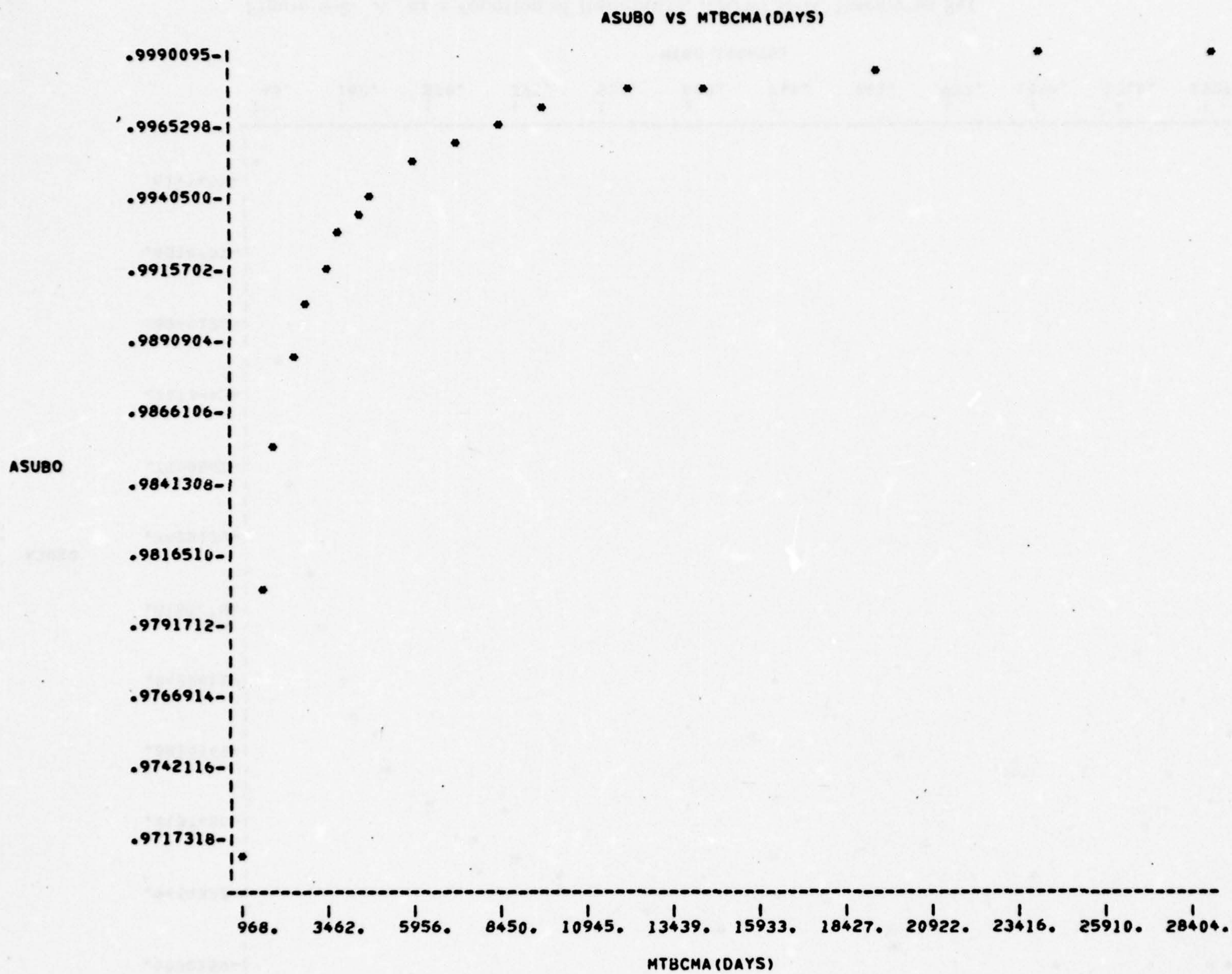


Figure 4-1. A_o as a Function of Reliability, AN/USM-117C Oscilloscope

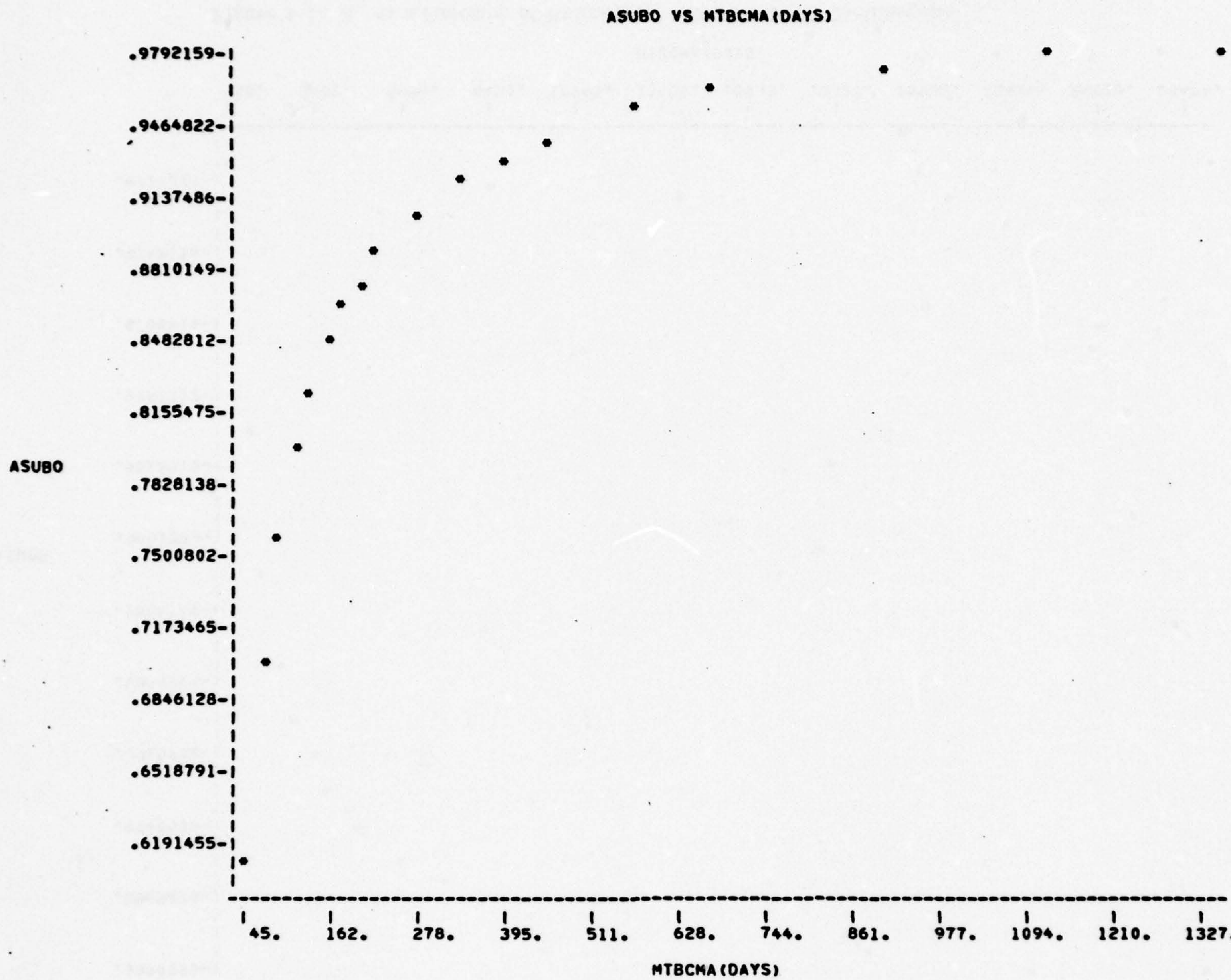


Figure 4-2. A_o as a Function of Reliability, AN/WLR-1C Receiving Set

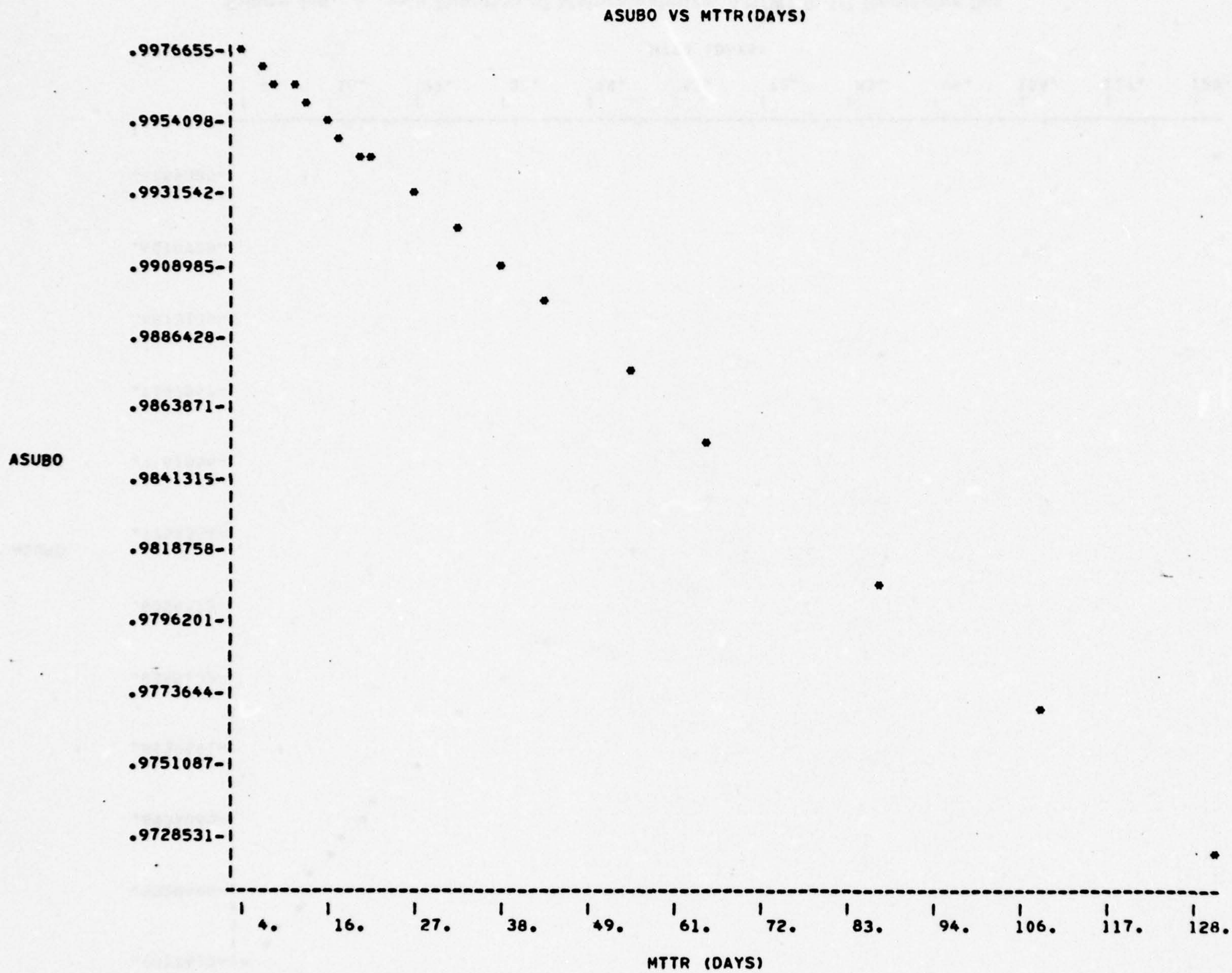


Figure 4-3. A_o as a Function of Maintainability, AN/USM-117C Oscilloscope

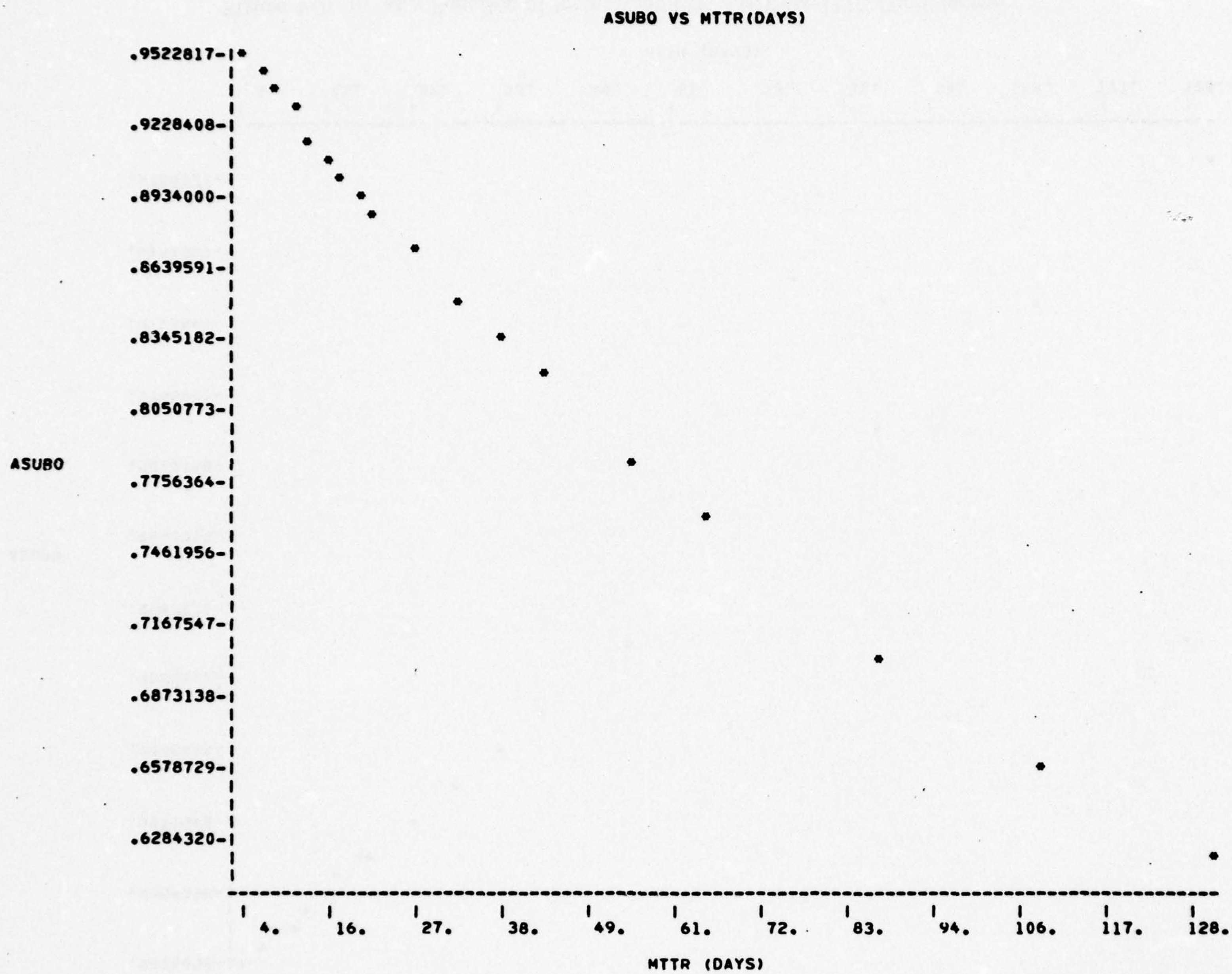


Figure 4-4. A_o as a Function of Maintainability, AN/WLR-1C Receiving Set

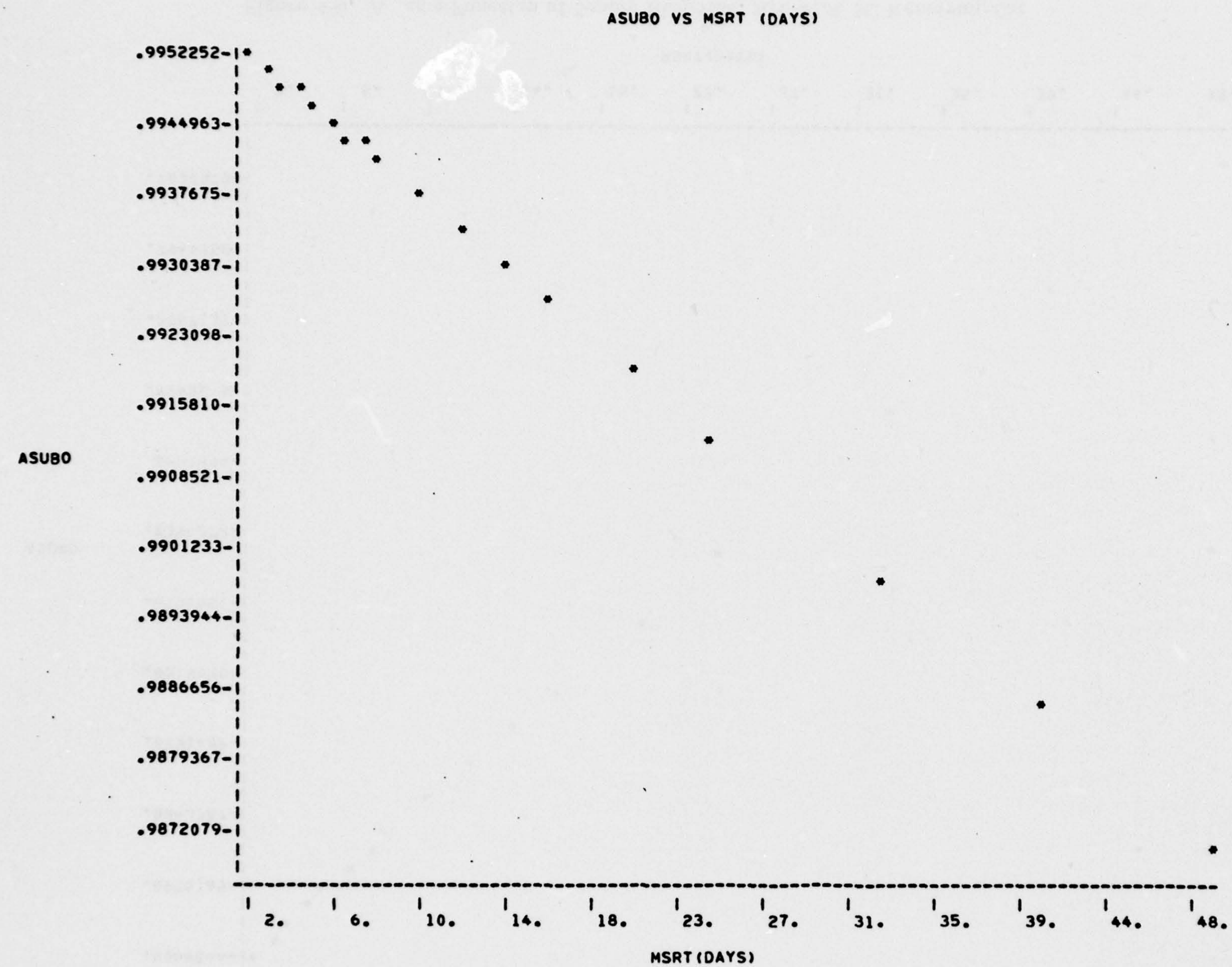


Figure 4-5. A_o as a Function of Supply Response, AN/USM-117C Oscilloscope

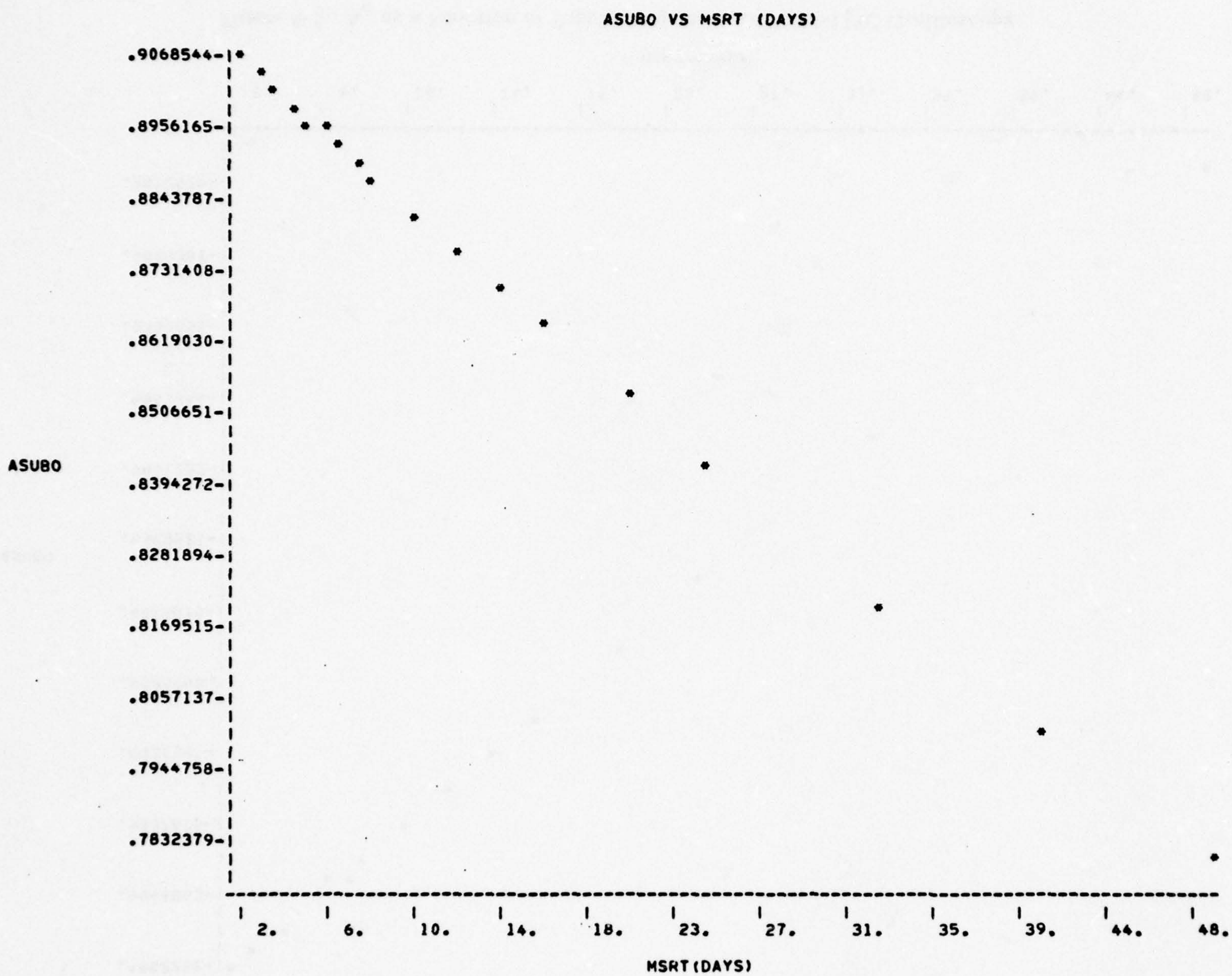


Figure 4-6. A_o as a Function of Supply Response, AN/WLR-1C Receiving Set

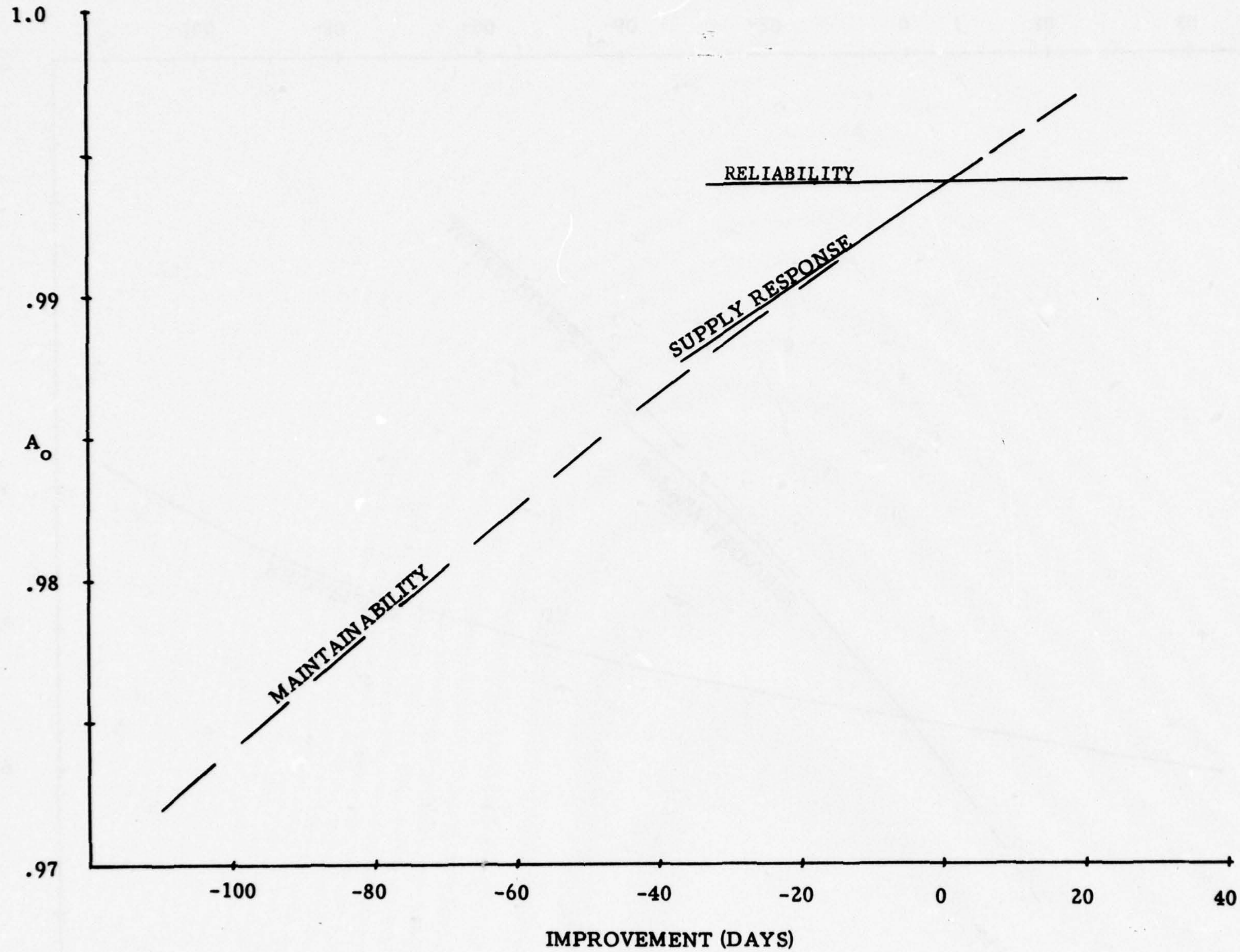


Figure 4-7. Impact on A_o of Varying Parameter Values, AN/USM-117C Oscilloscope

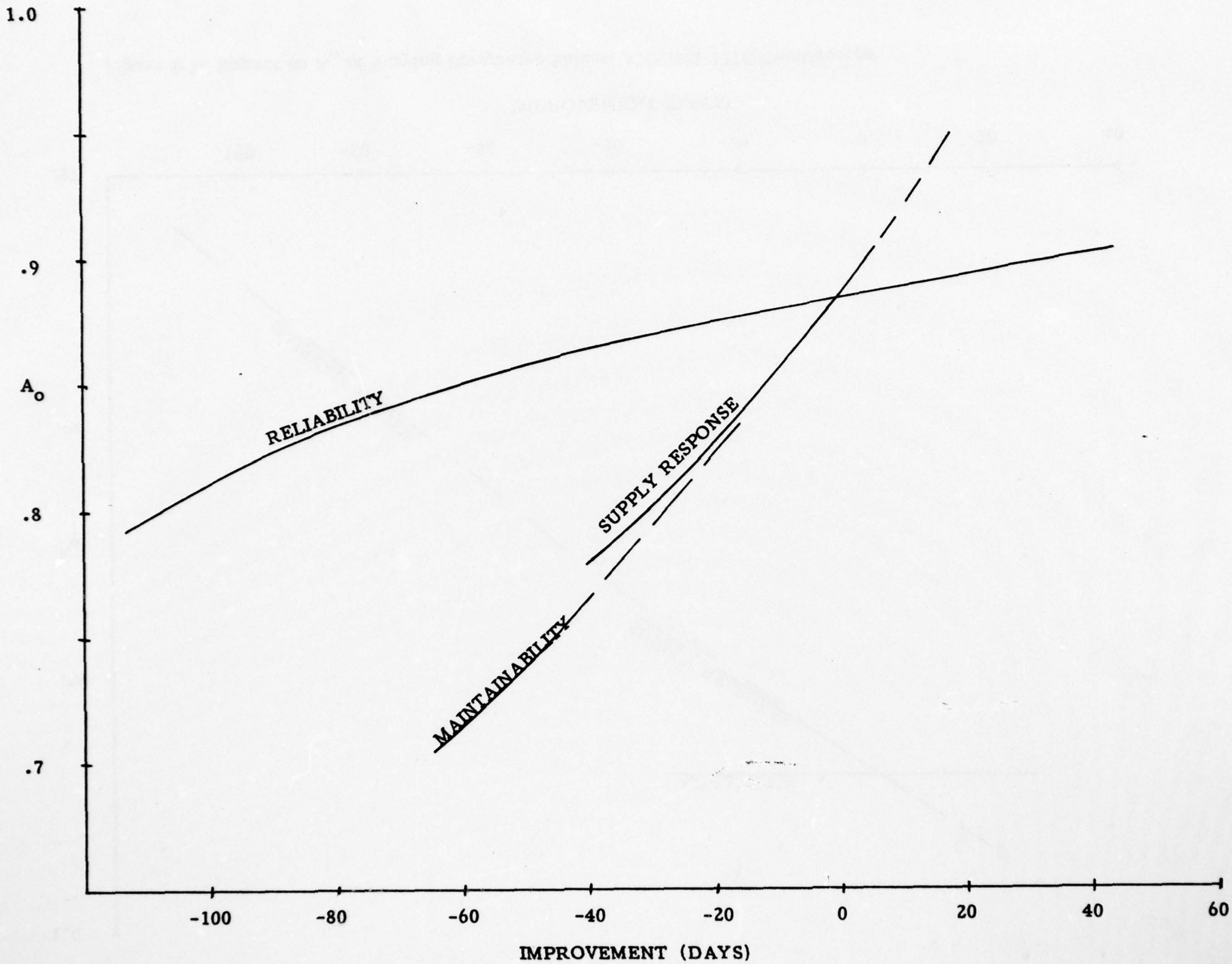


Figure 4-8. Impact on A_o of Varying Parameter Values, AN/WLR-1C Receiving Set

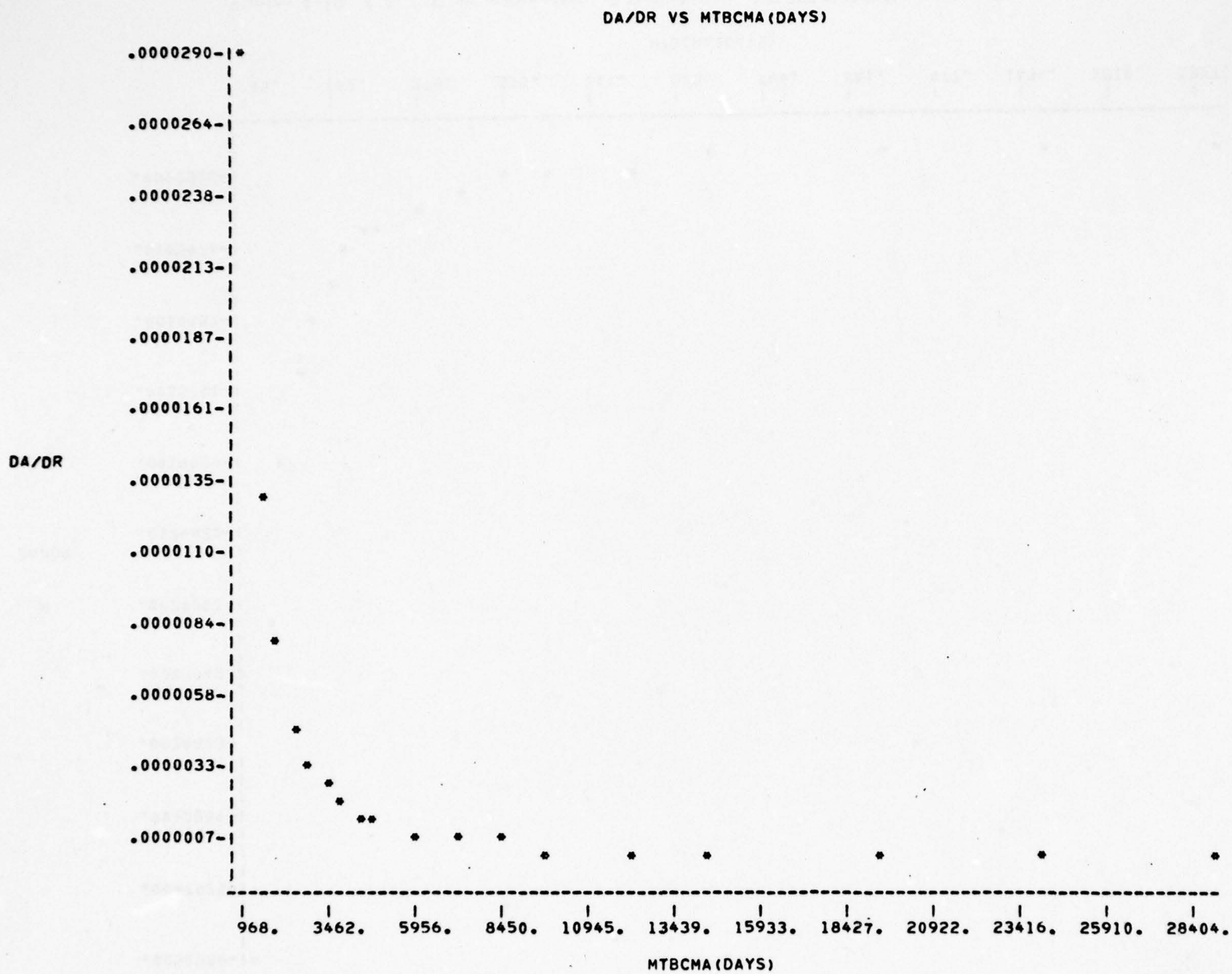


Figure 4-9. $\delta A_o/\delta R$ as a Function of Reliability, AN/USM-117C Oscilloscope

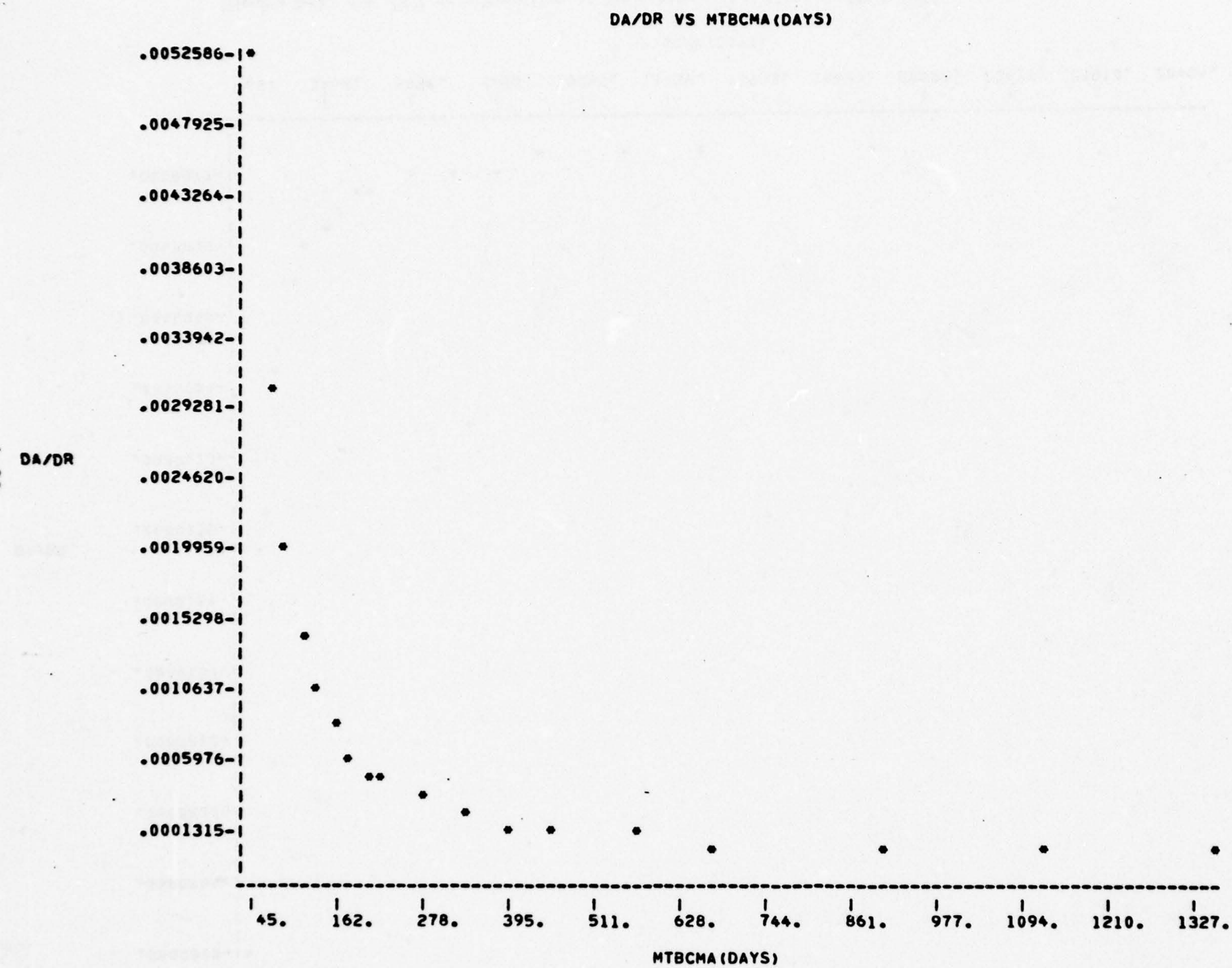


Figure 4-10. $\delta A_o / \delta R$ as a Function of Reliability, AN/WLR-1C Receiving Set

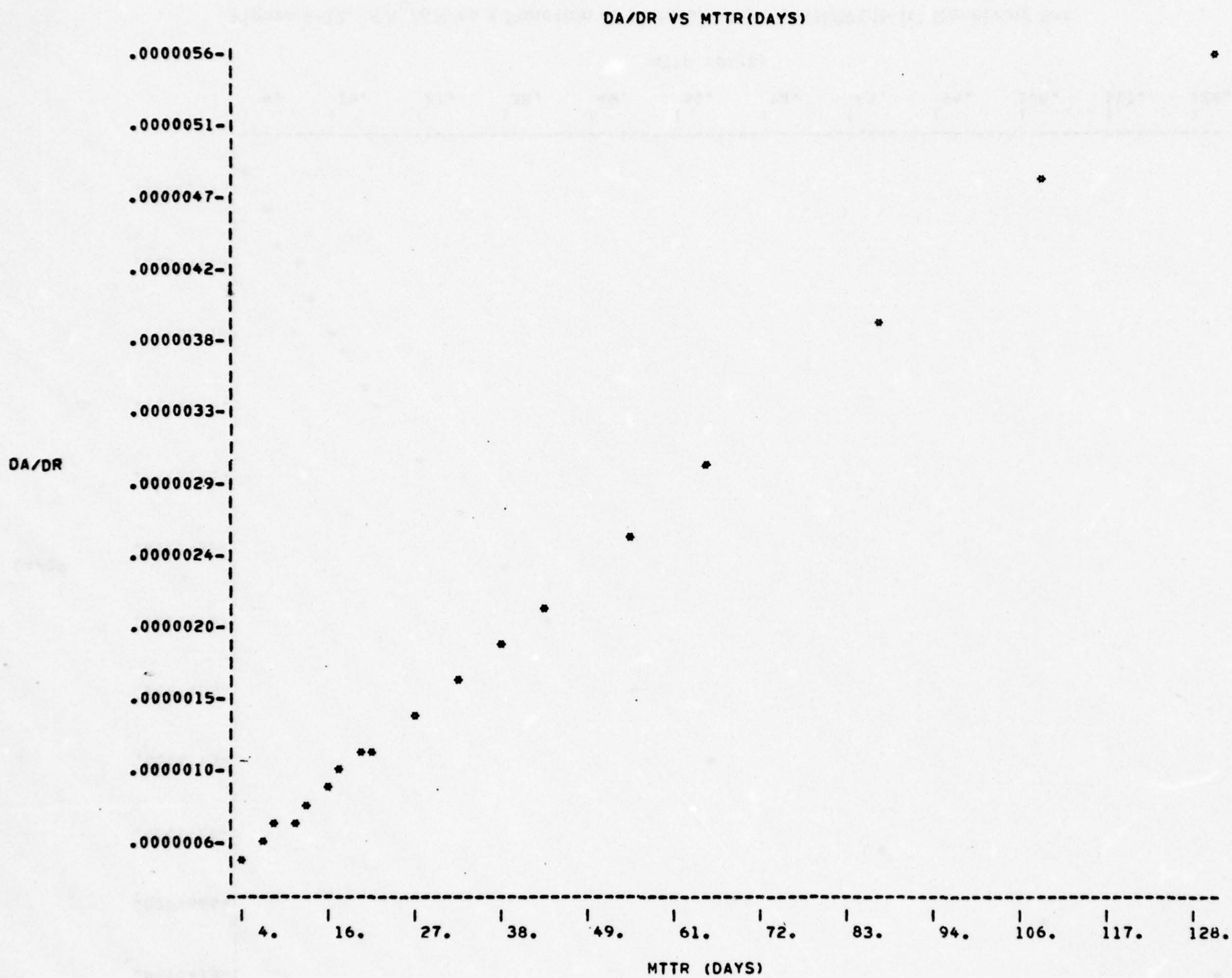


Figure 4-11. $\delta A_o / \delta R$ as a Function of Maintainability, AN/USM-117C Oscilloscope

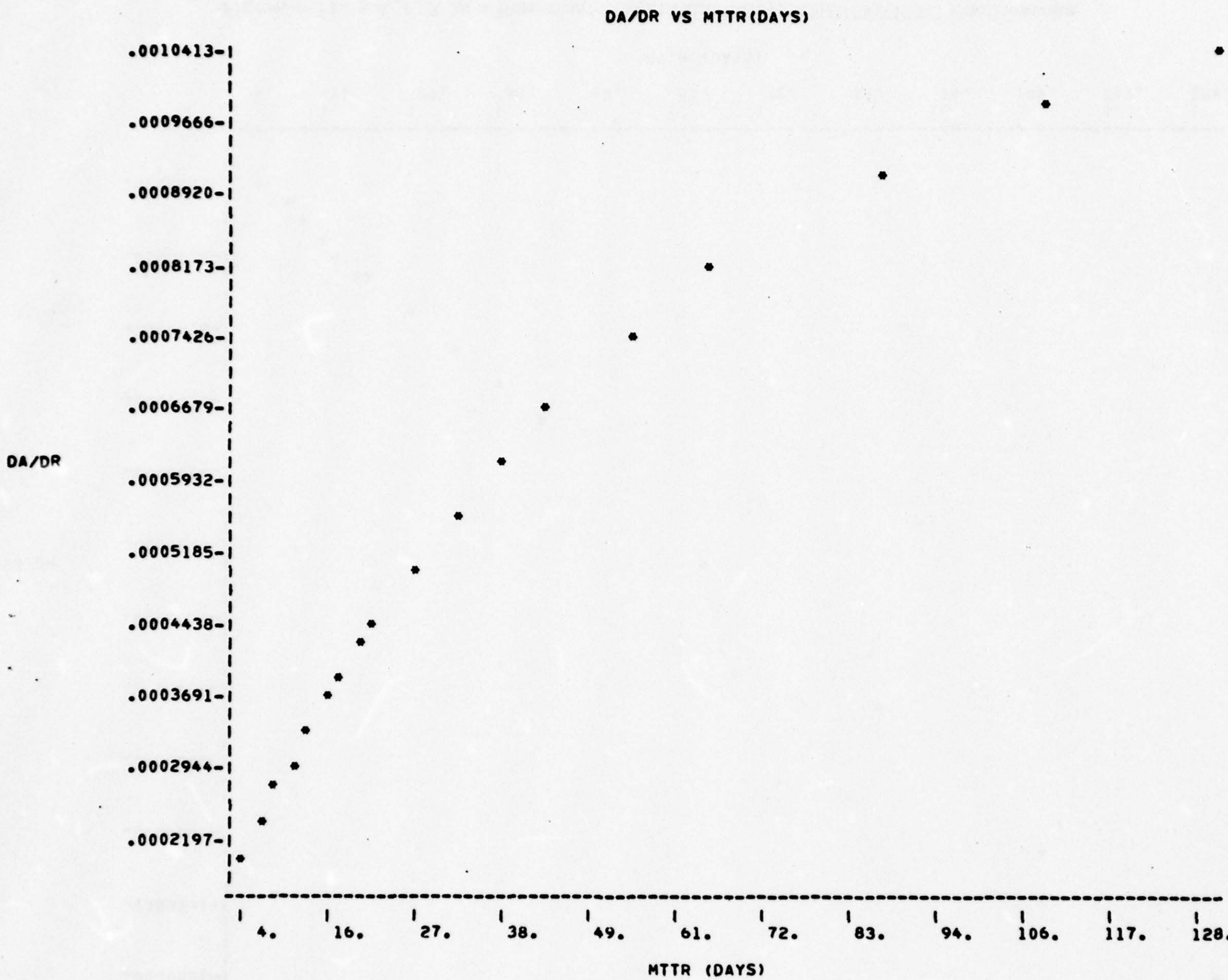


Figure 4-12. $\delta A_o/\delta R$ as a Function of Maintainability, AN/WLR-1C Receiving Set

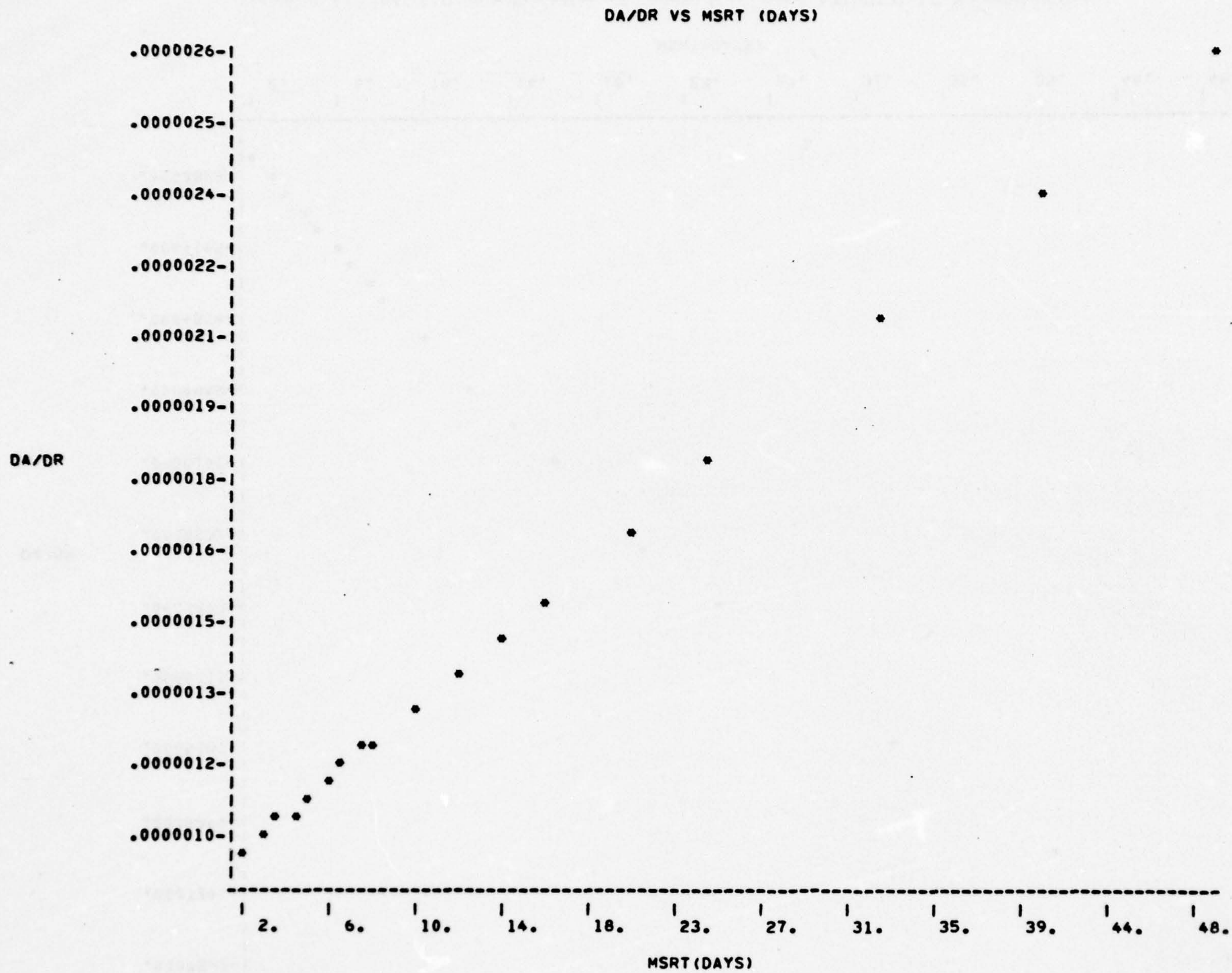


Figure 4-13. $\delta A_o / \delta R$ as a Function of Supply Response, AN/USM-117C Oscilloscope

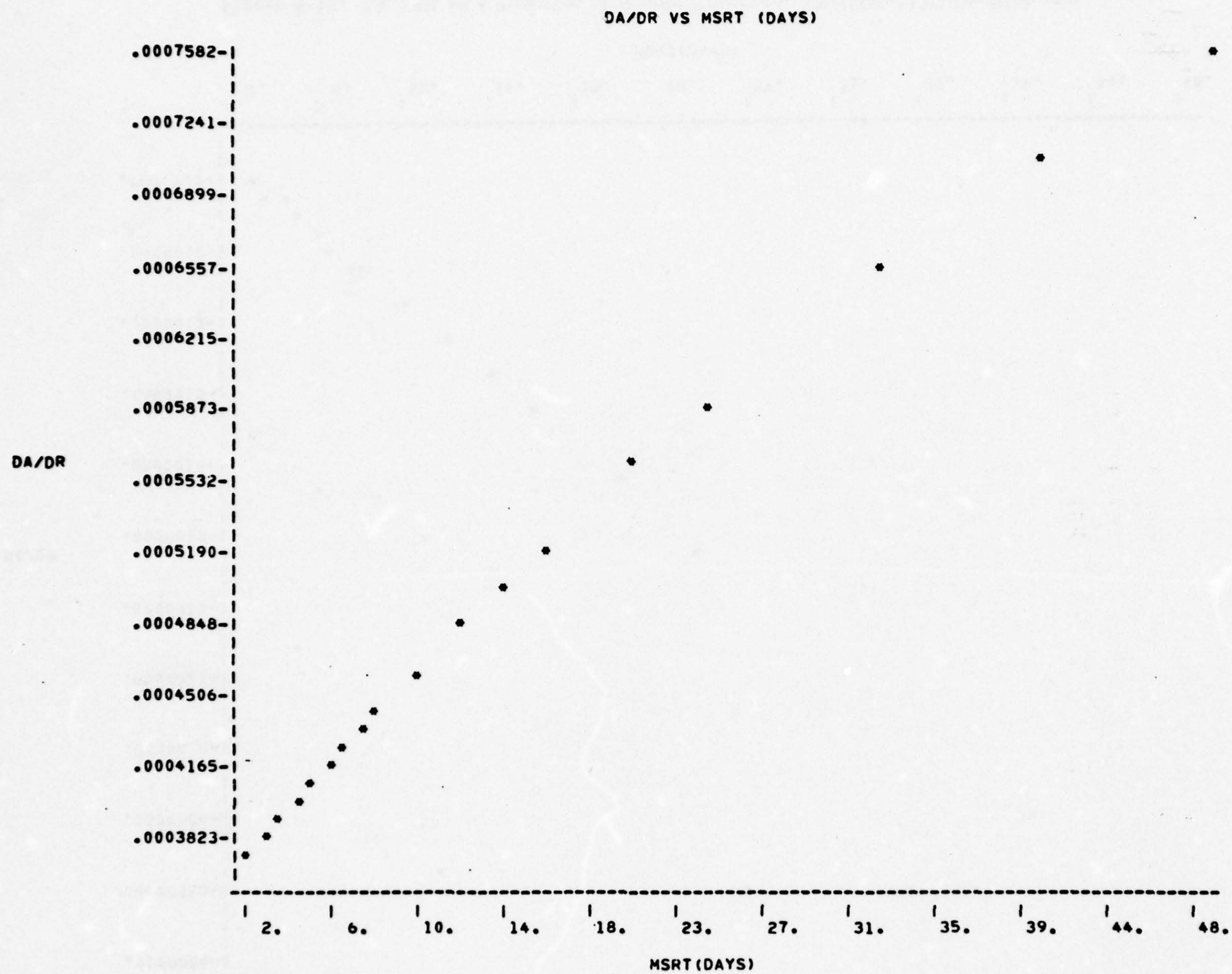


Figure 4-14. $\delta A_o/\delta R$ as a Function of Supply Response, AN/WLR-1C Receiving Set

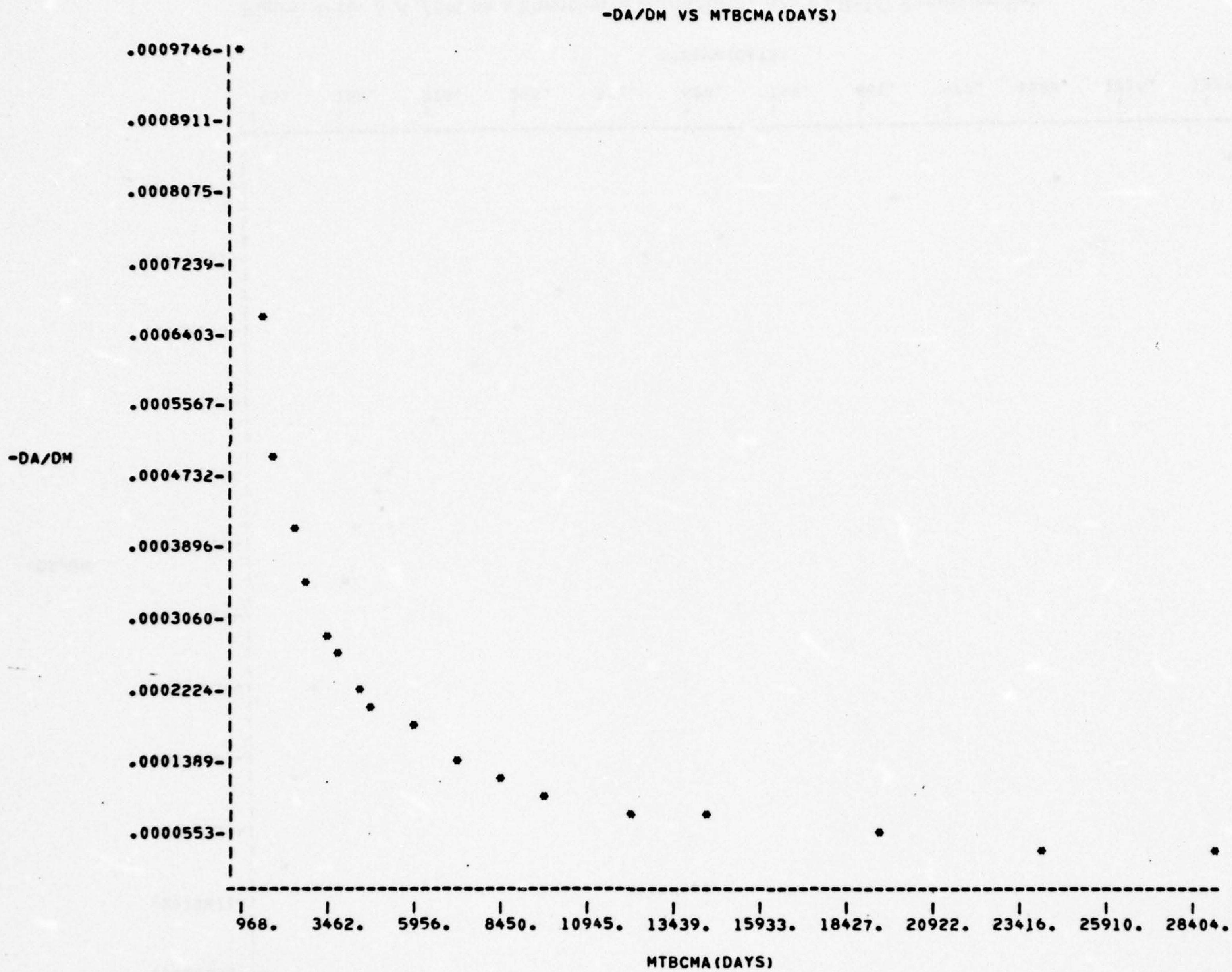


Figure 4-15. $\delta A_o/\delta M$ as a Function of Reliability, AN/USM-117C Oscilloscope

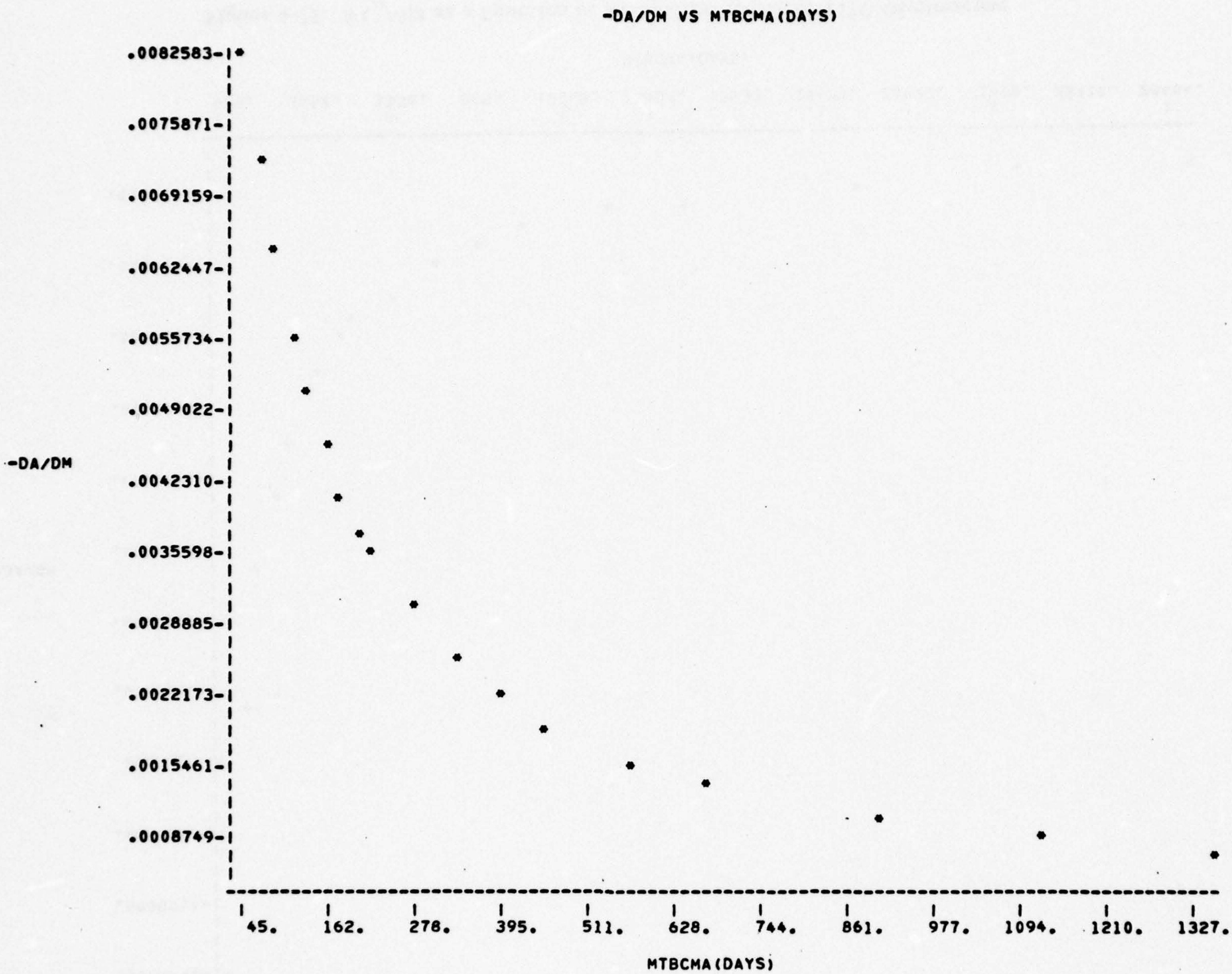


Figure 4-16. $\delta A_o/\delta M$ as a Function of Reliability, AN/WLR-1C Receiving Set

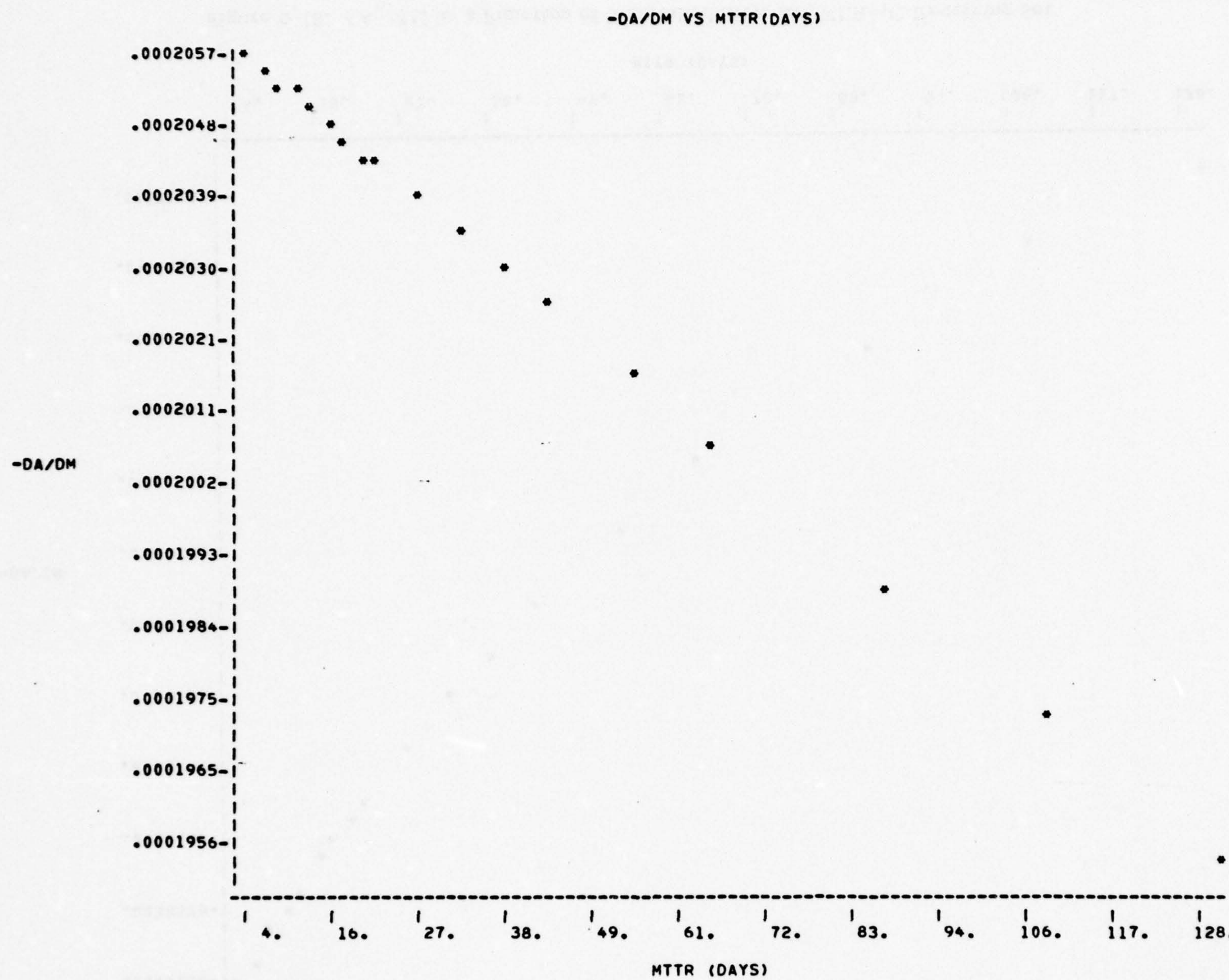


Figure 4-17. $\delta A_o/\delta M$ as a Function of Maintainability, AN/USM-117C Oscilloscope

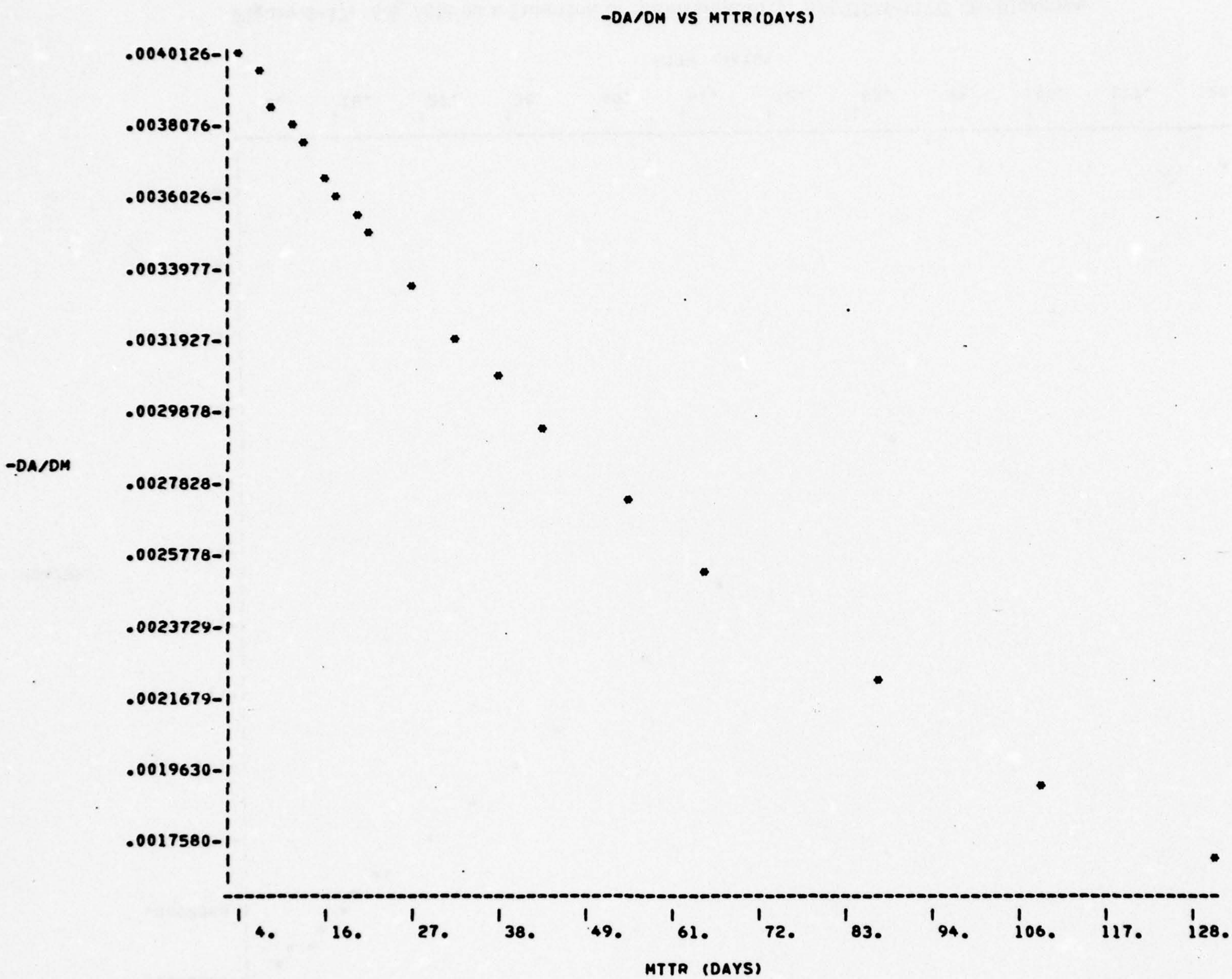


Figure 4-18. $\delta A_o/\delta M$ as a Function of Maintainability, AN/WLR-1C Receiving Set

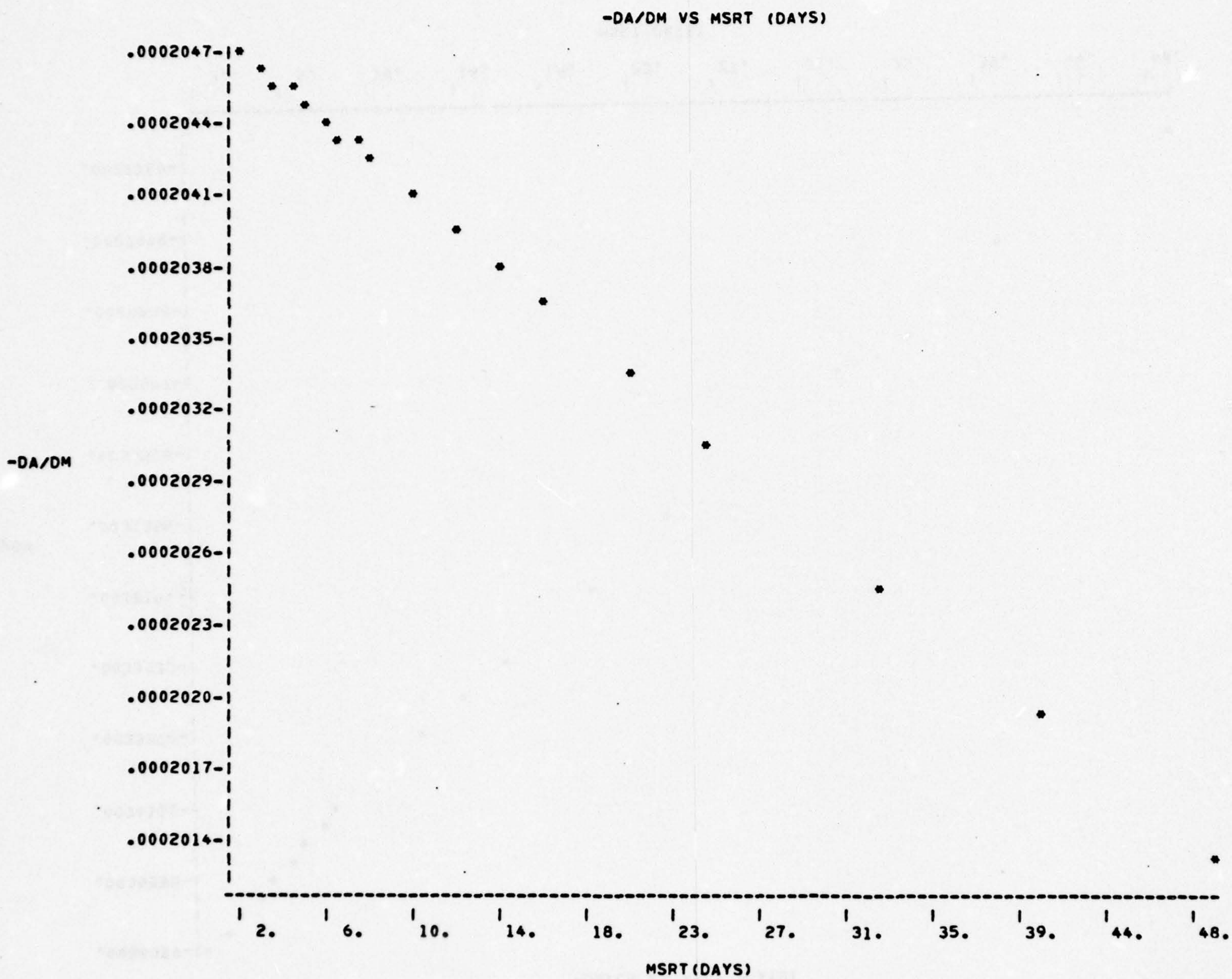


Figure 4-19. $\delta A_o/\delta M$ as a Function of Supply Response, AN/USM-117C Oscilloscope

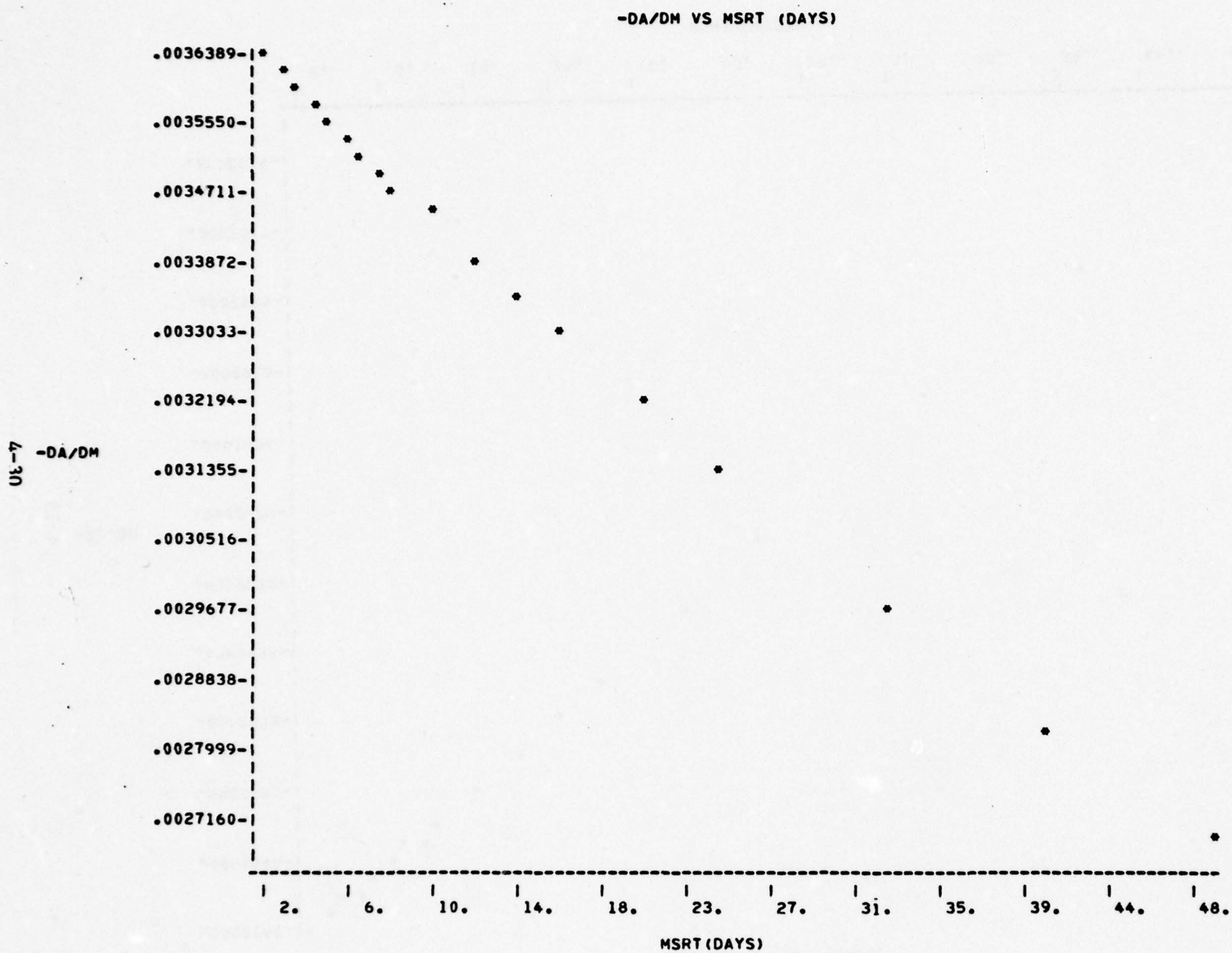


Figure 4-20. $\delta A_o/\delta M$ as a Function of Supply Response, AN/WLR-1C Receiving Set

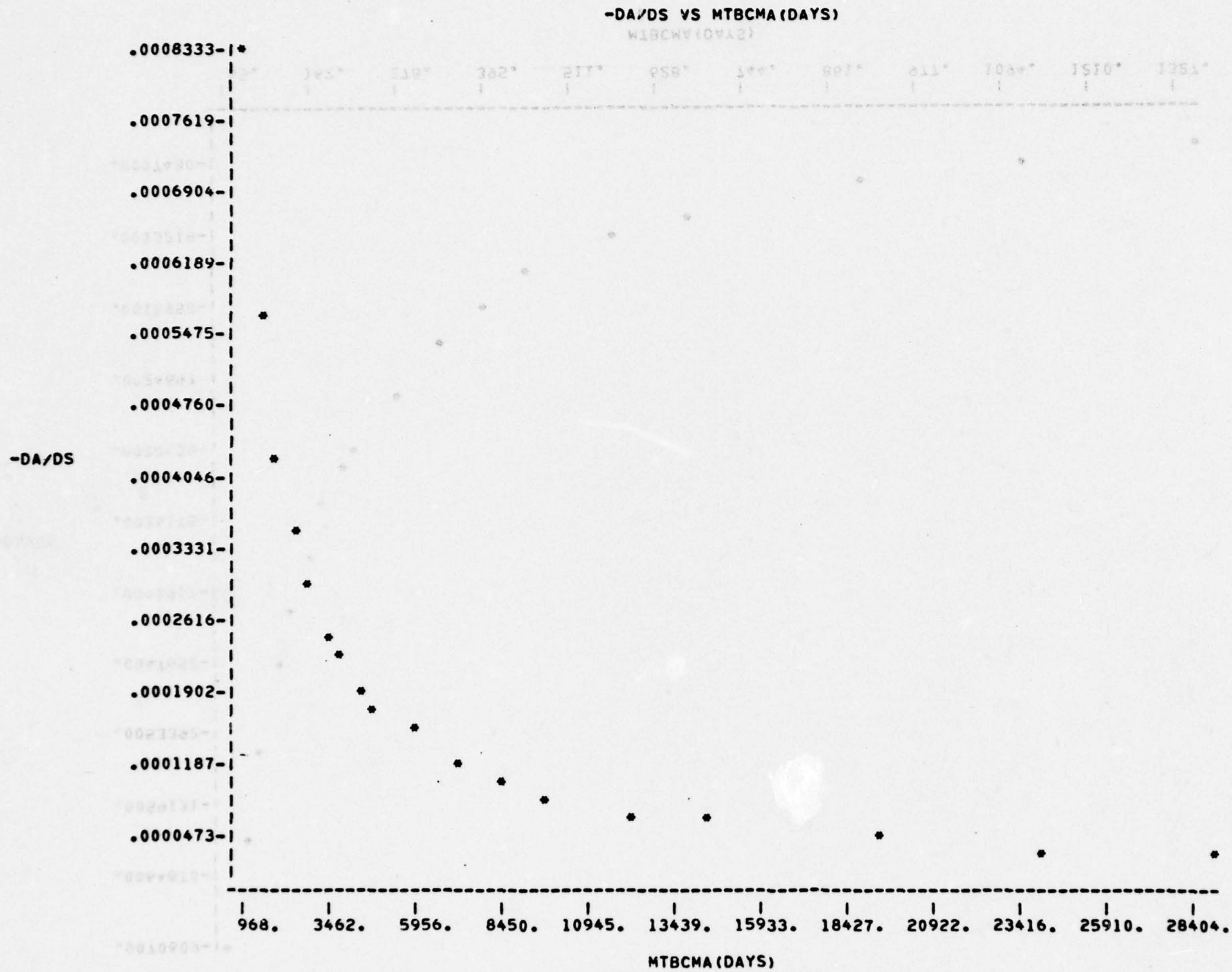


Figure 4-21. $\delta A_o/\delta S$ as a Function of Reliability, AN/USM-117C Oscilloscope

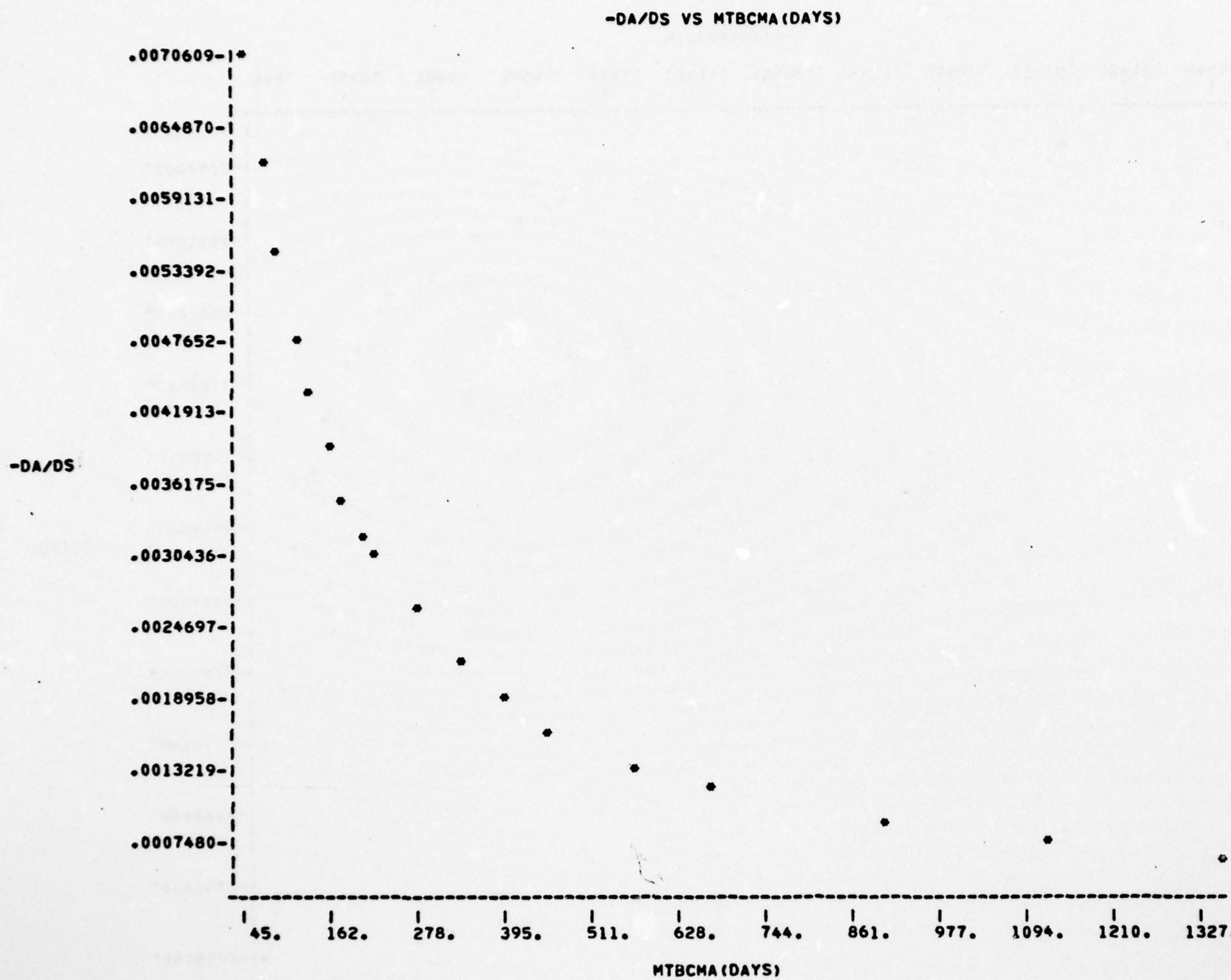


Figure 4-22. $\delta A_o / \delta S$ as a Function of Reliability, AN/WLR-1C Receiving Set

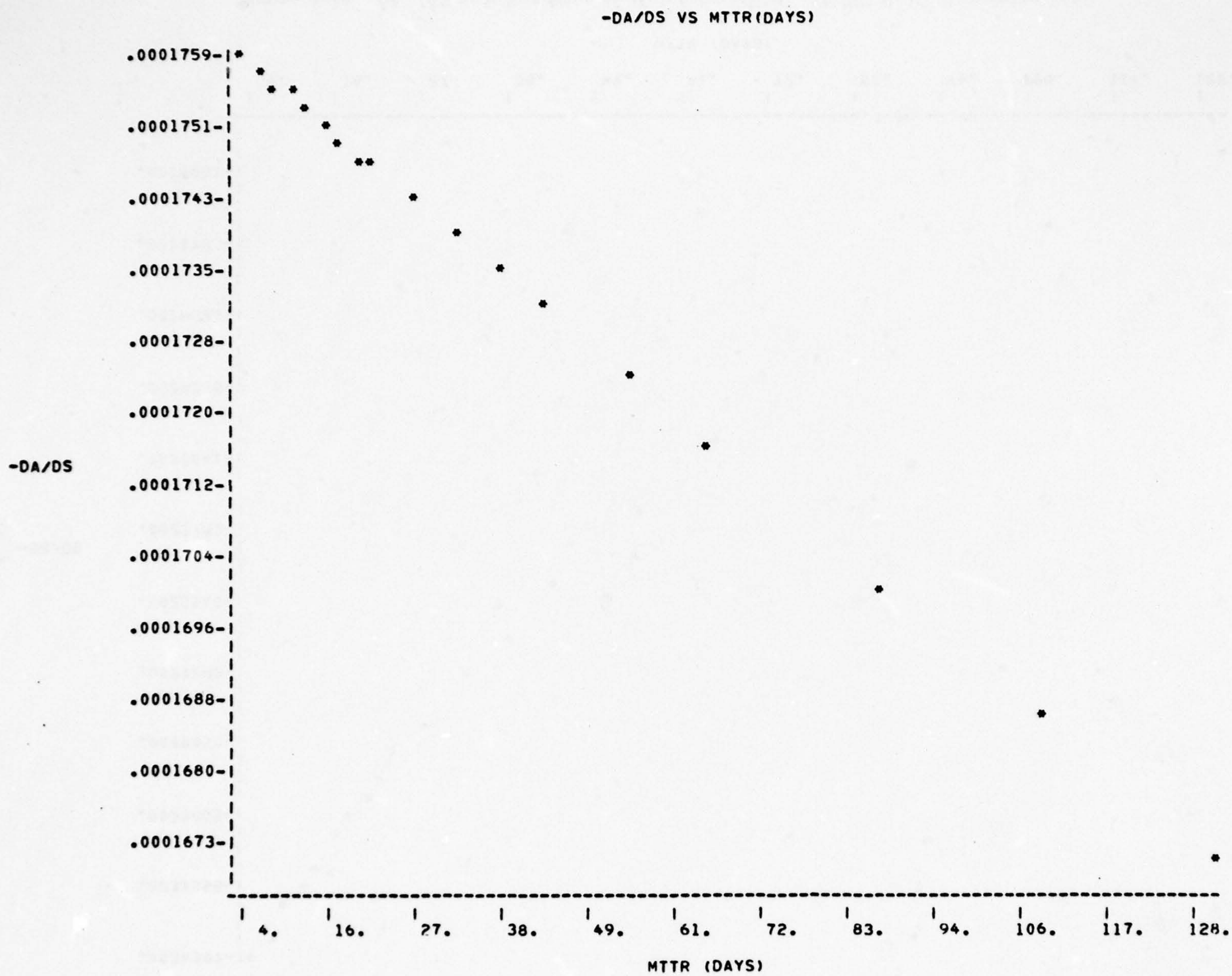


Figure 4-23. $\delta A_o / \delta S$ as a Function of Maintainability, AN/USM-117C Oscilloscope

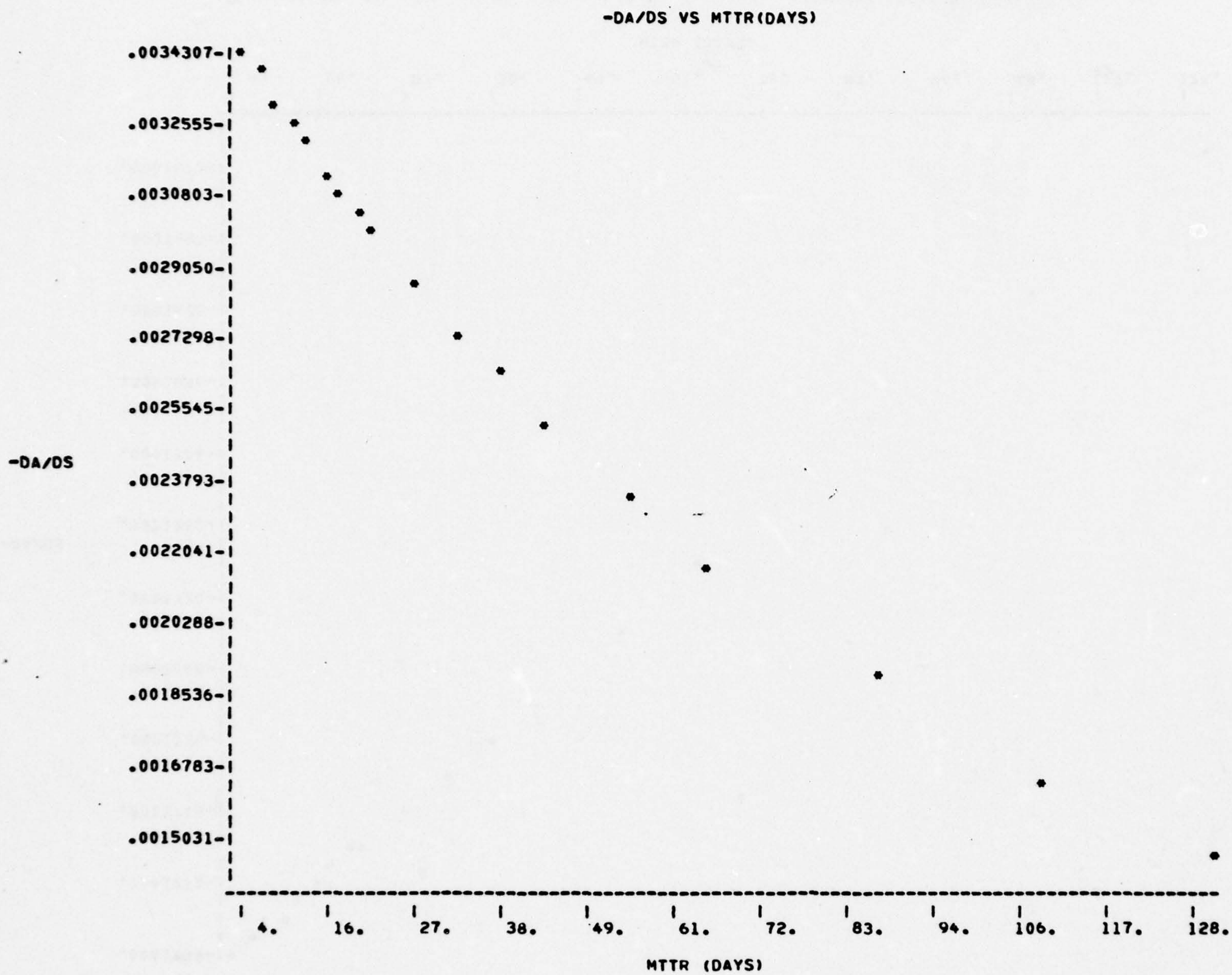


Figure 4-24. $\delta A_o/\delta S$ as a Function of Maintainability, AN/WLR-1C Receiving Set

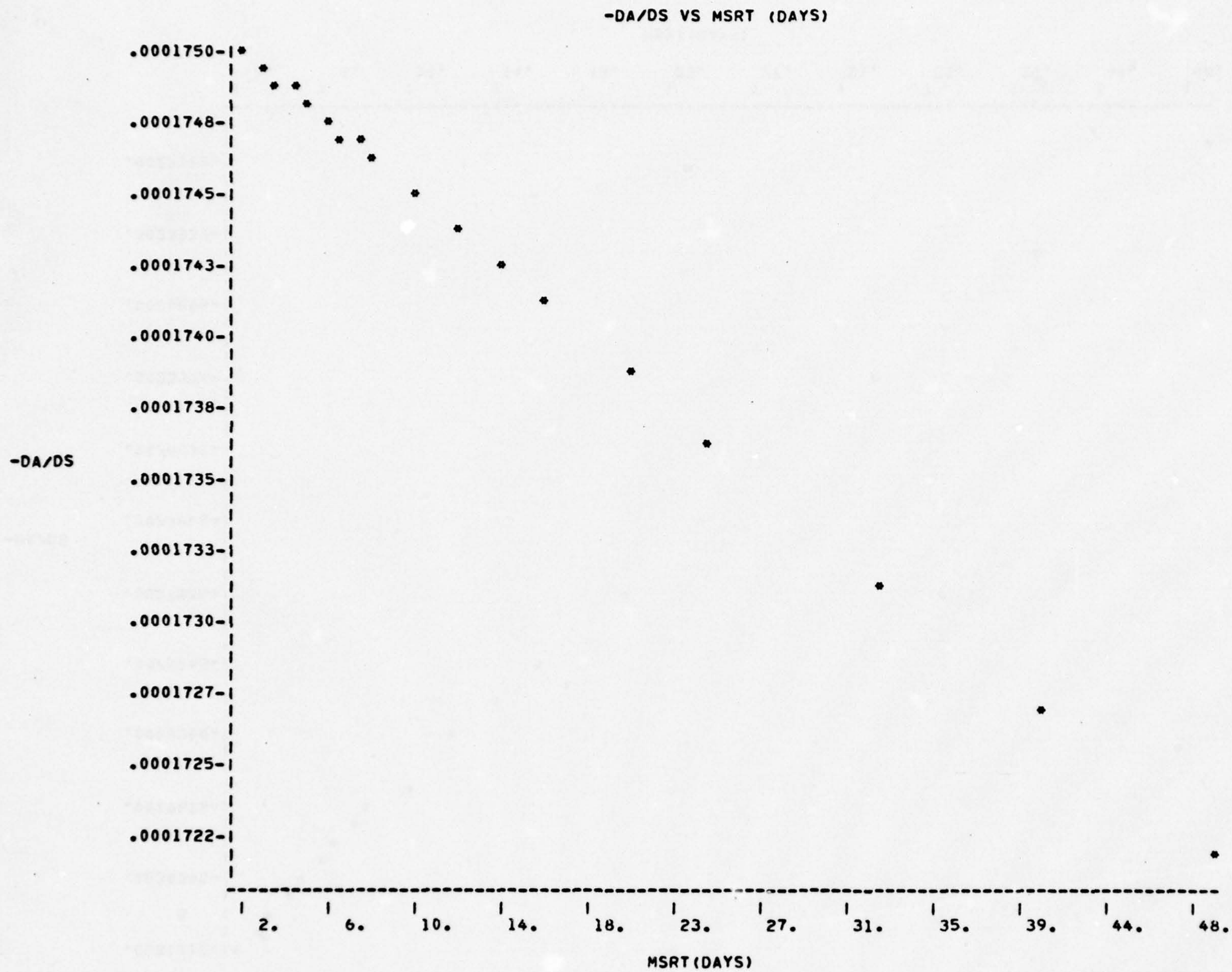


Figure 4-25. $\delta A_o/\delta S$ as a Function of Supply Response, AN/USM-117C Oscilloscope

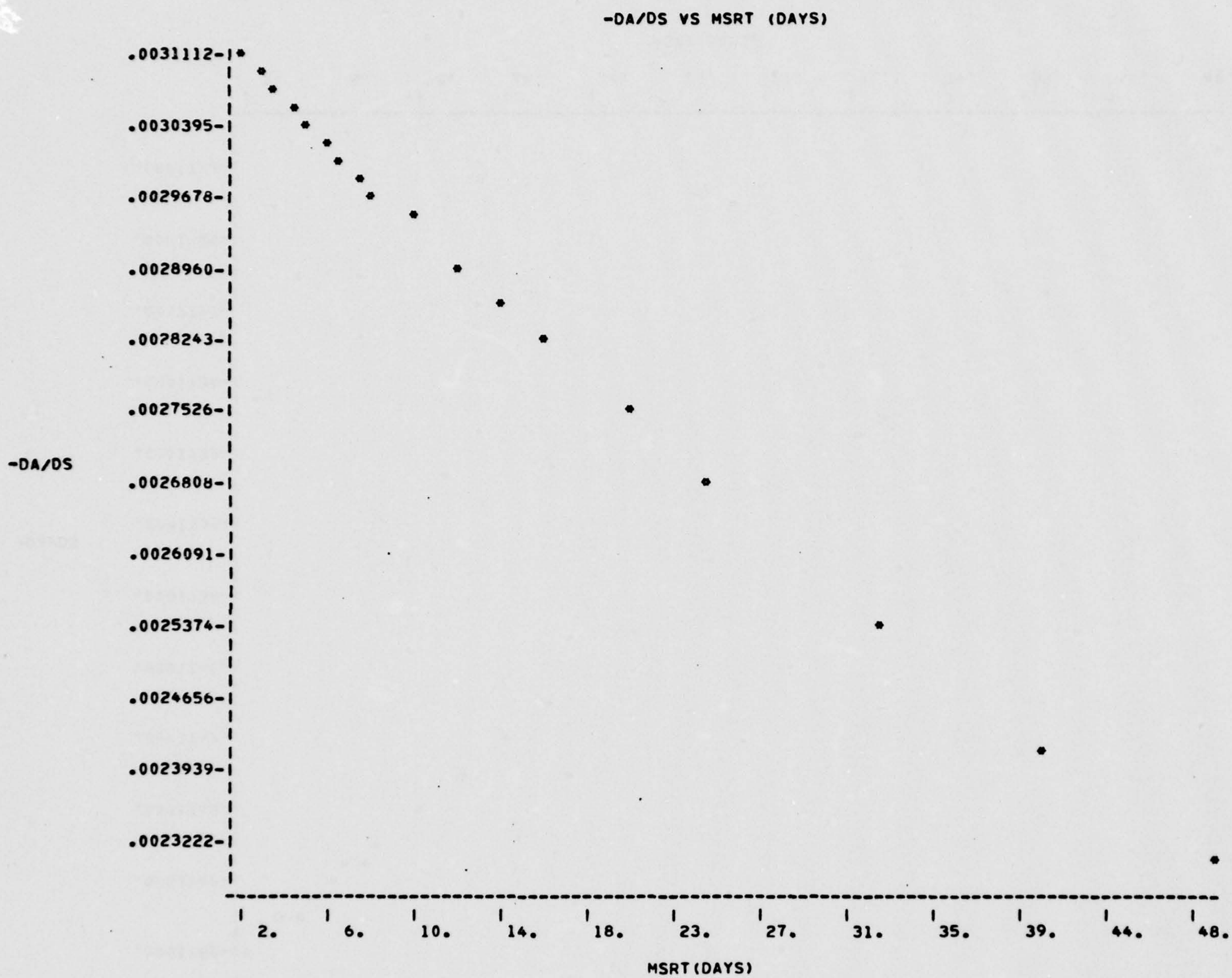


Figure 4-26. $\delta A_o / \delta S$ as a Function of Supply Response, AN/WLR-1C Receiving Set

MTTR (DAYS)	MTTR COST (DOLLARS)	COST OF MSRT + MTTR FOR ASUBO VALUES: .25	.40	.50	.70	.75	.80	.85	.90	.95	.99
4.36	999999	999999	999999	999999	999999	999999	999999	999999	999999	999999	999999
6.55	999999	999999	999999	999999	999999	999999	999999	999999	999999	999999	999999
8.73	16800	19371	19377	19384	19412	19427	19453	19504	19649	23806	999999
10.91	9600	12171	12177	12184	12213	12230	12258	12315	12501	999999	999999
13.09	7800	10371	10377	10384	10414	10432	10463	10529	10777	999999	999999
15.27	6982	9553	9559	9566	9597	9616	9650	9727	10077	999999	999999
17.46	6514	9085	9092	9099	9131	9152	9189	9279	9824	999999	999999
19.64	6212	8783	8789	8796	8830	8852	8893	9000	10028	999999	999999
21.82	6000	8571	8578	8585	8620	8643	8689	8819	12473	999999	999999
26.19	5723	8294	8301	8308	8347	8374	8431	8639	999999	999999	999999
32.73	5486	8057	8064	8072	8116	8150	8237	8872	999999	999999	999999
38.19	5365	7936	7943	7951	8001	8045	8180	999999	999999	999999	999999
43.64	5280	7851	7859	7867	7924	7981	8224	999999	999999	999999	999999
54.55	5169	7741	7748	7758	7835	7951	999999	999999	999999	999999	999999
65.46	5100	7672	7680	7690	7803	8193	999999	999999	999999	999999	999999
87.28	5018	7590	7599	7613	8133	999999	999999	999999	999999	999999	999999
109.10	4971	7544	7554	7571	999999	999999	999999	999999	999999	999999	999999
130.93	4941	7514	7526	7549	999999	999999	999999	999999	999999	999999	999999
MINIMUM MSRT		256	128	85	36	28	20	14	9	4	
MINIMUM MTTR		459	230	154	66	52	39	28	18	9	
MTTR + MSRT COST		7422	7481	7542	7803	7946	8179	8625	9819	23568	

Figure 4-27. Cost Trade-off, Maintainability vs. Supply Response

It is clear that this methodology may be used to evaluate the tradeoff between supply response and maintainability and, thus, lead to cost saving resource allocation decisions. Emphasis is needed on acquisition of cost data and determination of supply response and maintainability cost functions.

D. SUMMARY

A computer program called ASUBO ANALYZER was developed for rapid analysis of the impact on operational availability, A_o, of changes in reliability, maintainability and supply response. The program also provides an analysis of partial derivatives of A_o with respect to each of the three parameters. Two electronic equipments with widely different levels of reliability were selected to demonstrate the feasibility of the analysis methodology.

The program includes routines for determining the minimum cost trade-off between maintainability and supply response for each of several target levels of A_o. Cost functions were estimated for the purpose of demonstrating use of the program to obtain the minimum cost solution to the resource allocation problem.

V. ALTERNATIVE COSAL METHODOLOGY: INTRODUCTION

A. OBJECTIVE

Ship operational availability, A_o, is a function of, among other things, the availability of spare parts. The basic objective of the optimal A_o COSAL model is to establish shipboard spares in sufficient range and depth so that end-equipments can be maintained in ready-for-use condition according to given availability standards. Previous analytic COSAL models have been directed towards satisfying supply-oriented goals such as assuring given levels of protection against stockouts or minimizing expected backorders within a budget constraint. From an operator's point of view, however, the main interest is the extent to which an equipment is inoperative because of lack of needed spares. The optimal A_o COSAL model is designed to address this operational interest directly rather than indirectly through supply-oriented standards.

From an operator's point of view, an equipment should never be down waiting for spares. Needed items should always be immediately available. However, it is impractical to satisfy such an objective. Even if sufficient range and depth of spares to insure instant availability could be afforded (which is seldom the case), there would probably not be enough space aboard the ship to store the stock. The number of items involved would also present difficult stock management problems. Therefore, stock levels must be established within these practical constraints.

Recognizing the practical limitations on funding, the initial version of the optimal A_o COSAL model, as described in this report, is designed to satisfy either one of the following specific objectives:

- Determine the range and depth of spares which will maximize the operational availability of an equipment within a specified procurement budget.
- Determine the range and depth of spares which will achieve a given operational availability goal at minimum cost.

Later, the model may be extended to consider limited storage space and other constraints as well as constraints upon procurement budgets.

B. SCOPE OF PROBLEM

In order to satisfy stockage objectives based upon operational availability of equipments, a variety of factors must be considered in greater detail than in previous COSAL models. Of overriding importance are decisions based upon maintenance policies as to whether or not a given item is to be repaired or discarded upon failure and, if repaired, whether the repair will be accomplished by the ship's crew or at some intermediate or depot level repair facility. These "level of repair" decisions will control the list of candidates for COSAL stockage and will have an immediate impact upon equipment availability. Although deriving these decisions is beyond the scope of the COSAL model per se, a model which is based upon achieving A_o goals must be able to properly consider and interrelate any possible combination of level of repair designations (as reflected in SM&R codes) that may be assigned to items within an equipment.

Assuming level of repair designations are given by maintenance policies, the next two most important considerations are (a) the interrelationships of shipboard stocks and stocks positioned elsewhere in the supply system, and (b) the interrelationships of levels for the various items in the parts breakdown of the equipment.

To appreciate the importance of the first factor, consider an item that is a candidate for shipboard stockage but for which there are no assets elsewhere in the system (at the depot or wholesale level, in particular). If the ship runs out of stock, it must wait until resupply is obtained from a contractor and the equipment will be down for an extensive length of time. Compensation can be made, however, by increasing the COSAL level such that the chance of needing resupply is negligible. If system stocks are ample, on the other hand, the COSAL level can be reduced since resupply can be obtained in a relatively short time. Thus, the amount of stock at the wholesale level can directly affect the operational availability of the equipment aboard the ship and the amount of stock that should be carried in the COSAL.

The way in which equipments are broken down into constituent repairable assemblies and consumable parts is also important. Consider, for example, an assembly within the equipment which can be repaired (at least some of the time) at the ship level by the removal and replacement of included consumable parts. Here, there is a choice as to

which parts to stock and how much of each. If ample stocks of the repairable assembly are carried, then the assembly itself can be removed and replaced upon failure, returning the equipment to operational use. The repairable carcass can then be repaired at leisure without causing the equipment to be down. On the other hand, if there are no spare assemblies, then the failed assembly must be repaired before the equipment can be made operational in which case ample stocks of the included consumable parts would be desired. In general, the relative stock levels of assemblies and included parts impact directly upon the length of time an equipment is unavailable for use due to supply.

In addition to these two main considerations, a variety of other or subordinate supply-related factors can affect operational availability of equipments and must therefore be considered by an optimal A_o COSAL model. Included are procurement lead times, repair cycles, order and ship times for stock replenishment, and others. Since an A_o COSAL model is dependent upon system stocks which, in turn, depend upon the number of ships to be supported, the delivery schedule of ships in an acquisition program must be considered. Ships can vary in equipment configuration as well as in modifications of a given equipment type, and COSALs must be tailored accordingly.

C. TYPES OF OPTIMIZATION

Within the objectives of the optimal A_o COSAL model and the scope of the problem as outlined above, four basic types of optimization may be defined as follows:

- Pure Optimization. Stock levels at all locations, both ships and shorebased activities, are calculated simultaneously to satisfy the optimality criteria. This type of optimization may apply for new equipments whose stocks have not yet been established.
- Constrained Optimization. Stock levels at certain locations in the supply system (such as the wholesale system) are given and cannot be changed. Stock levels at remaining locations (such as ships) can be optimized subject to the given stocks. This type of optimization applies when particular stockage policies or existing stock levels must be recognized and complied with in the optimization procedure.

- <u>Enhanced Optimization</u>. Stock levels at some or all locations are specified by existing policies but may be selectively increased by the optimizing procedure in order to increase the operational availability of equipments. This type of policy might apply where ships have already been stocked according to current COSAL policies but may be augmented by optimization.
- <u>Budget Reclama</u>. Stock levels at all locations are given,but those at some locations must be reduced due to funding limitations. Here, the stock reductions are to be made so as to minimize the impact upon shipboard A_o.

The optimal A_o COSAL model described in subsequent sections is capable of accomplishing all four of these optimizing procedures. Collectively, they enable the implementation of the model in context with existing stockages, policies and supply procedures,and facilitate a planned transition to the new policies.

D. DEFINITION OF A_o

In previous studies, a variety of definitions and formulas for operational availability of equipments have been developed. However, for purposes of the optimal A_o COSAL model, a particular definition has been established which relates directly to the analytic formulation of the model.

In the operative definition of A_o, it is assumed that an equipment fails and becomes unavailable for use at random points in time. At each failure, an average mean-time-to-repair (MTTR) is incurred which is independent of the supply status of parts in the equipment. An additional mean supply response time (MSRT) is incurred at each failure which depends upon the stockage status of included parts and represents, in effect, delays caused by lack of needed parts. The MSRT is subject to control by the optimal A_o COSAL model, but the MTTR is assumed to be given and constant. The equipment operational availability is then defined by the following formula:

(1) $$A_o = 1.0 - (\text{FAIL})(\text{MTTR} + \text{MSRT}),$$

where

A_o	=	fraction of calendar time that an equipment is available for use
FAIL	=	average number of equipment failures per unit time

MTTR = average length of time the equipment is down for maintenance

MSRT = average length of time the equipment is down for supply

To illustrate the meaning of this formula, consider an equipment that fails 2 times per month on the average and, at each failure, the MTTR is .03 months (about 1 day) and the MSRT is .10 months (about 3 days). Then,

$$A_o = 1.0 - (2)(.03 + .10) = .74$$

Thus, the equipment would be available for use 74% of the time, on an average. Note that if an infinite amount of supply were provided (MSRT = 0), the expected A_o is .94 which is the highest attainable A_o by means of stock level adjustments alone.

The above formula for A_o can easily be related to the "classical" formulation given by:

$$(2) \qquad A_o = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR} + \text{MSRT}}$$

To illustrate the connection between formulas (1) and (2), suppose that the equipment operates 200 hours per month and the mean time between failures (MTBF) is 100 operating hours. Then, 2 failures per month will be expected as in the numeric example previously given. Suppose that MTTR = .03 and MSRT = .10 as before.

To obtain equivalence, it is first necessary to change MTBF from operating hours to an equivalent operating time (in months) between failures which excludes the time the equipment is inoperative. Thus, the mean calendar time between failure occurrences is .5 months (since there are 2 failures per month). This is reduced by .13 (MTTR + MSRT) to give a mean operating time of .37 months between failures. Substituting this value in (2) for MTBF gives:

$$A_o = \frac{.37}{.37 + .03 + .10} = .74$$

which is the same as that given by (1).

In general, the MTBF in equation (2) must be interpreted as mean operating time (in a consistently defined time unit) between failures. If $\overline{\text{MTBF}}$ represents the mean calendar time between failures, then

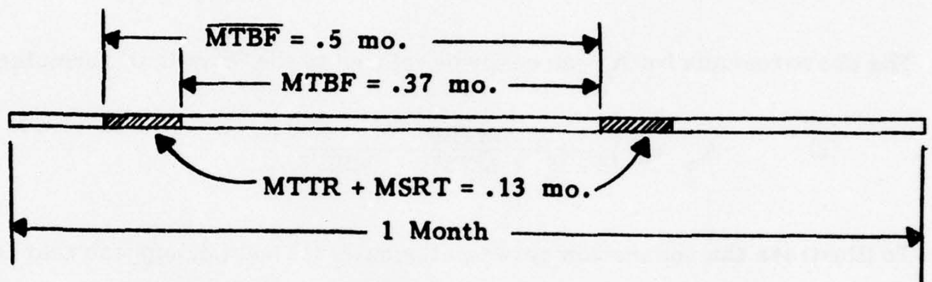
$$MTBF = \overline{MTBF} - (MTTR + MSRT)$$

which, when substituted in (2) gives

$$A_o = \frac{MTBF - (MTTR + MSRT)}{\overline{MTBF}} = 1.0 - \frac{(MTTR + MSRT)}{\overline{MTBF}}$$

$$= 1.0 - (FAIL)(MTTR + MSRT),$$

thereby establishing the equivalence of the two formulations for A_o given by formulas (1) and (2). This relationship is further clarified by the following diagram based upon the numeric example given above:



In the diagram, the 2 failures per month are indicated, and the shaded area represents time the equipment is inoperative at each failure occurrence. The unshaded area therefore represents the fraction of time the equipment is operational and is calculated as 1.0 - .26 = .74.

E. MODELLING APPROACH

In formulating the modelling approach for the optimal A_o COSAL model, two requirements of the overall problem were recognized. The first requirement was to provide a representation of the supply environment including the multi-echelon, multi-indenture, material flows caused by SM&R designations, lead times, repair cycles and other factors mentioned above. The second requirement was to calculate COSAL levels according to the A_o optimizing criterion within the given supply environment.

To facilitate the model development, a model previously developed was used to provide a representation of the supply environment and to satisfy the first requirement. This model, LSEE (Logistics Support Economic Evaluation), has been designed to provide a comprehensive and adaptive representation of supply operations in support of one or more equipments described in terms of their parts breakdown. LSEE also includes procedures for calculating COSAL levels according to several policies currently used by the Navy. A LSEE User's Guide is available for more detailed description of the model, reference (4).

To accomplish the second requirement, the calculation of optimal COSAL levels, specialized routines were embedded in the larger LSEE model. From the LSEE point of view, the optimal COSAL model was nothing more than an addition to its existing cadre of COSAL models. Thus, of the total optimal A_o COSAL modelling effort (in terms of computer programming), LSEE was able to provide perhaps 90% of the requirement. However, the level of logical complexity of the remaining 10% was considerably greater than that of LSEE due to the highly technical nature of the mathematical formulation of the optimizing procedure.

In addition to the optimizing routines embedded in LSEE, special reports were developed to give results of the optimizing procedure. These reports are described in a later section of the report.

F. CASE STUDIES

In order to test the operation of the optimal A_o COSAL model and to demonstrate results of the procedure, two test cases were developed. The first test case consists of a seawater pump with two of them on a ship. The second test case considers the AN/UYK-7 computer of which there is one per ship. For both cases, only one ship was considered. Other simplifying assumptions were imposed as described in later sections of the report. In each case, levels and resulting operational availability measures computed by the model are compared against those of current Navy COSAL models.

G. CONTENTS

In the next section, the overall structure of the optimal A_o COSAL model is given, including portions provided by the LSEE model. In general, the overall capabilities and

limitations of the model are established in this section and the operation of the model is discussed.

In Section VII, the two case studies are presented in terms of descriptions of the equipments involved, input data, assumptions, and results of the calculations. Implications and significant points of the results are discussed, particularly with respect to comparisons of the different COSAL models.

Section VIII contains several conclusions and recommendations as derived from the limited amount of analysis and case studies conducted in the current project effort. Technical descriptions of the optimization model and the supply system representation provided by LSEE are given in Appendices B and C, respectively.

VI. ALTERNATIVE COSAL METHODOLOGY: COSAL MODEL STRUCTURE

In this section, the overall structure of the optimal A_o COSAL model is described in terms of main features, assumptions and constraints, input data requirements, computation methodology, and types of output reports.

A. PARTS BREAKDOWN

The optimal A_o model considers one or more equipment types in terms of hierarchies of included parts similar to that shown in Figure 6-1. All of the parts are simultaneously evaluated and COSAL levels are calculated by considering the way in which the parts are interrelated in the hierarchy structure. A given part may appear in several places in a particular equipment type and/or in several different end-equipments. The several appearances of a common item are considered collectively in establishing the COSAL level rather than separately with a level being calculated for each appearance. There are no restrictions as to the number of equipment types, included parts, and levels of indenture within the parts hierarchy except as may result from the size of the computer used.

Different A_o or budget goals may be set for each end-equipment defined by input data. Separate cost-effectiveness curves, as defined later, may be constructed for each equipment or a single curve for a collection of equipments. By defining test equipment used for on-board maintenance in terms of parts breakdowns in the same way as for the operational equipment, consolidated spares for support of both kinds of equipment can be calculated with or without separate A_o/budget goals.

B. SUPPORT SYSTEM

The logistics system providing worldwide maintenance and supply support is considered by the optimal A_o COSAL model in terms of supply and maintenance interrelationships as depicted by the example in Figure 6-2. Locations in the support system may be operating sites and/or logistics support sites. An operating site is

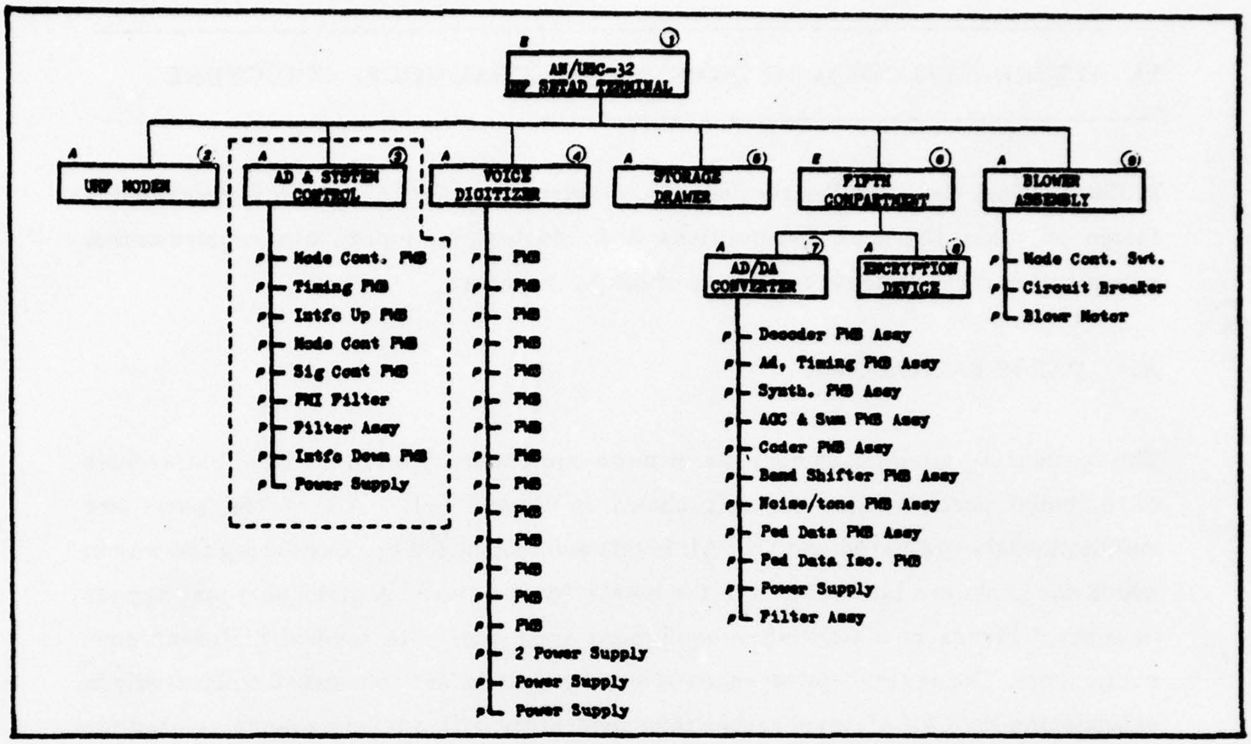


Figure 6-1. Example Parts Breakdown

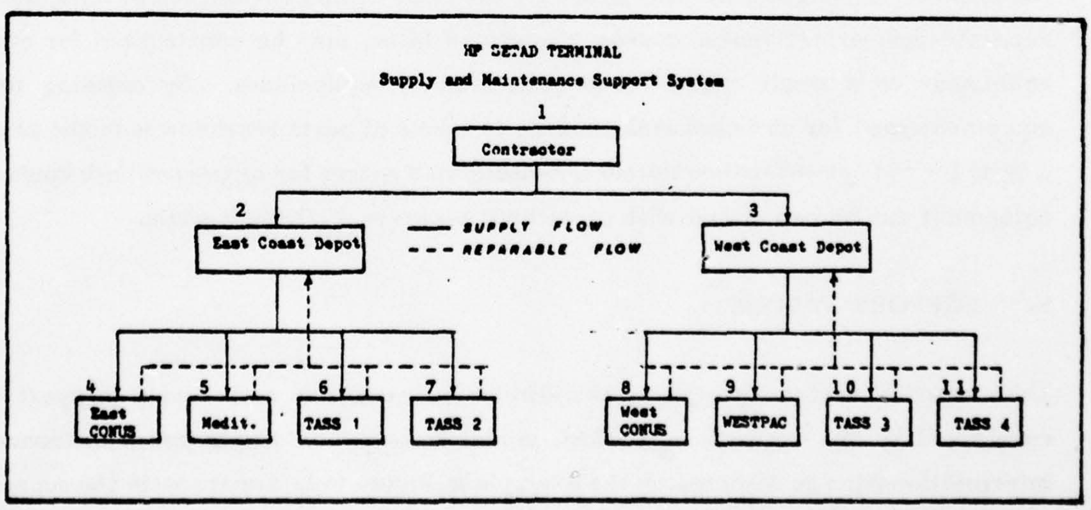


Figure 6-2. Example Logistics Support System

defined as one which possesses and operates one or more units of the equipment(s) being considered. It may provide some or all of the required maintenance support for units of the equipment it operates and, in addition, provide support for units located at other sites. A support site may offer only supply and/or maintenance services to operating sites.

Sites accomplishing repair, overhaul or maintenance functions are further classified as to the scope of services provided. Organizational level maintenance, provided by operating sites, normally consists of a limited amount of malfunction diagnosis and correction. Intermediate maintenance activities (IMA), which may or may not have operational units of the equipment, provide a broader range of maintenance services. Depot level maintenance activities, which usually do not operate the equipment, provide a full spectrum of repair and overhaul services. Organizational and IMA locations may send repairable items to higher repair facilities for repair.

Locations in the support system may be defined exactly, in general terms, or combinations thereof. Particular activities for which COSAL levels are to be calculated can normally be specified by name. Higher level activities providing supply and/or maintenance support, however, often cannot be exactly identified and must be described in general terms. As locations are defined, flows of repairables may be established by considering, for each location, where repairables are to be normally sent if beyond the site's repair capability. Similarly, for each location, identifications may be made as to where resupply is to come from to replace losses (scrap/discard) or items sent elsewhere for repair. Often, the supply source is general in nature, such as the "wholesale system." In other cases, a higher level maintenance activity to which repairables are sent also provides serviceable units as replacements and can so be identified as the supply source.

Often, several activities are identically the same with respect to all logistics support functions. For example, a squadron of ships may consist of several frigates which are all the same in terms of the number of equipments, equipment utilization and support, and support system interrelationships. If so, the several activities may be treated collectively as a single activity insofar as model inputs and operation are concerned, with the number of actual sites represented being given as an input factor. However,

if the different activities involved in such generic location designations differ in any regard, such as the times at which the sites begin operational use of the equipment (phase-in schedule), they must be separately identified.

In some cases, several equipments may be considered where each equipment has a significantly different support system in terms of included activities and their logistics interrelationships. In such cases, several support systems may be constructed (like the one illustrated in Figure 6-2), with associations between support system and equipment/components being given by input data.

The various operating sites in the system for which COSALs are established are identified as to the type of COSAL policy that applies. Some or all sites may be designated for computation according to the optimal A_o criterion. Some of the sites, however, may be designated for calculation by one of the following current Navy policies:

- Conventional SPCC
- .15 FLSIP
- .25 FLSIP
- TRIDENT

For sites to be stocked by a current policy, the optimization model will account for their impact upon sites for which optimal A_o levels are computed (they interrelate via system stocks which support all operational sites and which affect, as previously discussed, COSAL levels at sites subject to the optimization criterion). Also, the model will produce measures of achievable operational availability of equipments subject to the current policies.

C. ASSUMPTIONS AND CONSTRAINTS

The initial version of the optimal A_o COSAL model has several limiting assumptions and/or constraints which will be removed or alleviated in later versions. The most important of these are as follows:

1. It is assumed that resupply at any location (including the wholesale system) is on a one-for-one basis. Whenever an item is lost from inventory, a

replacement order is made. Thus, batch ordering or ordering according to economic order quantity (EOQ) policies are excluded.

2. A continuous resupply opportunity is assumed for all locations. Thus, a ship can place an order for resupply whenever needed and receive the resupply an order-and-ship-time later if available from its supply source.
3. Each failure of an equipment is assumed to be due to only one included part. Thus, to repair the equipment whenever it fails, only one part need be removed and replaced.
4. Two echelons of stockage are assumed – the user level and the system or wholesale level. Lateral resupply among users (e.g., from ship to ship) is assumed not to occur. System stocks are assumed to be available to all users for resupply and the order-and-ship-time is assumed to be independent of where the wholesale stocks are physically located.
5. Actual failures of the equipment are assumed to be independent of the equipment's operational availability. In reality, as A_o decreases, the equipment is operated less and hence the failure frequence will decrease.
6. It is assumed that the mean time to repair (MTTR) includes all of the time that the equipment is inoperative due to non-supply related causes. The total MTTR is assumed to be a constant given for each repairable item.

D. LOR/SM&R CODE ASSIGNMENTS

Designations of which items in an equipment are repairable and where the repair is accomplished are provided by input data to the model. The initial version of the model contains a convention for such assignments which is commonly used in LOR models (models designed to make level of repair decisions). It is assumed that one of the following LOR designations is made for each item in the equipment:

1 - Organizational level repair
2 - Intermediate maintenance activity (IMA) level repair
3 - Depot level repair
4 - Discard

NOTE: The above convention was developed for specific use in the LSEE model and does not necessarily agree with the LOR coding conventions contained in MILSPECS on the subject of LOR coding.

If an item is assigned an LOR code of 1, organizational repair, this does not mean that all failed units of the item are repaired aboard the ship. Several other factors given by input data control the fraction of all failures that are actually repaired at the organizational level. First, a scrap factor may be applied to designate the fraction of all failures that are not economically repairable at any repair level and must be discarded or salvaged. Of the remainder, another input factor designates the fraction which is beyond the capability of maintenance (BCM) at the organizational level and must be sent to a designated IMA or depot for repair. Still another factor specifies the fractions of BCM quantities that are sent to the IMA and depot, respectively.

If an item is assigned an LOR code of 2, IMA level repair, all repairable carcasses are assumed to be sent to an IMA facility for further disposition. There a certain fraction may be scrapped, and the rest may be repaired either at the IMA or at a depot according to a given BCM rate assigned to the IMA.

If an item is assigned an LOR code of 3, it is assumed that all repairable carcasses are sent to the depot for disposition, either being scrapped according to a given scrap rate or repaired. Items assigned an LOR code of 4, discard, are assumed to be not economically repairable and are thrown away at the location where they are removed and replaced.

Instead of the four LOR codes defined above, the optimal A_o model permits the maintenance codes which are part of the Navy's SM&R (Source, Maintenance and Recoverability) code to be assigned. There are two maintenance codes, one designating the lowest maintenance level authorized to remove and replace or use the item and the other designating the lowest maintenance level having a complete capability of repairing the item. The code assignments also indicate whether the item is consumable or repairable. In the model, the SM&R maintenance codes, if assigned, are translated during input processing to the four LOR codes defined above. However, there are some unavoidable inconsistencies in this translation which must be considered in the assignment of SM&R maintenance codes or else recognized in interpreting results of the model.

For example, an assembly may be assigned SM&R maintenance codes which are translated into LOR code 3, depot level repair. A consumable part within the

assembly may be assigned SM&R maintenance codes which indicate the part may be removed and replaced at organization level but which is translated to code 4, discard. According to the LOR code definitions given above, the assembly would always be sent to the depot for repair and the ship would have no use for the consumable part, which is contrary to the intent of the SM&R codes for the part. To compensate for this inconsistency, the assembly should be assigned SM&R maintenance codes which translate to an LOR code of 1, organizational repair, with BCM rates being appropriately assigned to reflect the percentage of assembly failures that can, in fact, be repaired at organizational level.

Other inconsistencies can arise in translating SM&R maintenance codes to LOR codes. It is planned to revise the model at a later time so that it will operate correctly according to either coding scheme without translating SM&R codes to LOR codes. Meanwhile, this model limitation must be recognized inasmuch as results of the model can be significantly affected by the LOR/SM&R code assignments.

E. INPUT DATA REQUIREMENTS

Input data requirements for operation of the overall optimal A_o COSAL model (including LSEE inputs needed to describe the equipments and their logistics support environment) may be organized into several functional groups. These groups and their included data elements are defined as follows:

1. Item Data. Data elements in this group may be input on an item basis for the equipments and included parts. Some of the elements are input only for the end-equipments, particular included components, or included repairable assemblies. Others are provided for all parts.

   Description – the name of the item and/or its part number. This is not operational in the logical processes of the model and is used only for identification purposes on output reports.

   Item Type and Reference Number – codes assigned to equipments and repairable assemblies for use in establishing parts hierarchy relationships.

   Delivery Schedule Identification – for equipments and/or selected components, the identification of the applicable delivery (phase-in) schedule.

Support System Identification – for equipments and/or selected components, the identification of the applicable logistics support system.

Operating Factor – for equipments and included repairable assemblies, the fraction of time that the item operates whenever its next higher assembly operates (for equipments, the next higher assembly is the ship itself). This may also be entered in terms of average operating hours per month.

Units per Next Higher Assembly – the number of units of the item per next higher assembly.

Unit Cost – an estimate of the unit procurement cost of the item.

MTBF/BRF – the mean time to failure, in number of operating hours. Instead of MTBF, a Best Replacement Factor (BRF) may be entered in terms of expected number of failures per year. The model converts BRFs to MTBFs by dividing into 8766, the number of hours in a year.

LOR/SM&R Code – either an LOR code or the SM&R maintenance codes as defined and discussed in the previous section.

MRU – the minimum replacement unit for the item.

Essentiality Code – either the conventional SPCC essentiality code (vital, non-vital) or the FBM Military Essentiality Code (MEC) as defined for TRIDENT application. (Note – this code is not used by the optimal A_o COSAL model. It is entered to calculate levels according to current Navy COSAL models.)

COG – the applicable cognizance code for the item. This is used to assign values to certain system factors as given below.

2. Location Data. Data in this group define and describe locations that operate the equipment and/or provide supply/maintenance support. Included data elements are as follows:

Description – the name of the location and/or its Unit Identification Code (UIC). This data is not operative in the logical processing of the model and is used only for identification purposes in output reports.

Location Identification Number – a sequentially assigned number to identify the location. This number is referenced by other data elements defined below.

Type Code – a code identifying the general maintenance level of the location (organizational, intermediate, depot).

Support System Data – data defining the relationship of the location to the overall logistics support system. Up to six different support systems may be defined, with data provided to identify the location's position in each system. For each system, the following three factors are defined:

Supply Source – the identification (location identification number) of the activity from which resupply is normally obtained.

IMA Destination – the identification of the activity to which repairables are sent for intermediate level repair if beyond the maintenance capability of the given location.

Depot Destination – the identification of the activity to which repairables are sent for depot level repair if beyond the maintenance capability of the given location.

3. Phase-in Schedule. This group of data defines the delivery schedule of equipments being considered. As many different schedules may be defined as necessary, with each schedule being associated with particular equipments. Usually only one delivery schedule is defined to represent the ship phase-in schedule under the assumption that delivery of included equipment occurs at the same times. Within each schedule, the following four data elements are defined for each delivery occurrence:

Delivery Date – the calendar month and year for the delivery. The model assumes first use of the equipment commences at the mid-point of the given month.

Location – the identification (location identification number) of the location receiving delivery of the equipment.

Number of Units – the number of units of the equipment being delivered at this time. This is set to 1 if the ship phase-in schedule is being defined.

Operating Factor – the fraction of time this increment of equipment is expected to operate; the average number of operating hours per month may be entered instead. If a ship phase-in schedule is being defined, this represents the average fraction of time the ship is expected to be operational.

4. Optimizing Specifications. This group of input data includes factors that specify the type of optimization to be accomplished at the various defined lcoations and establish A_o or budget goals to be achieved. For each end-equipment and type of user (for which a different COSAL is to be calculated), the following data elements are provided:

Optimization Type – a code indicating the type of optimization to be accomplished (1 = pure, 2 = constrained, 3 = enhanced, 4 = budget reclama).

MTTR – a default value for the mean time to repair as applied to the equipment as a whole.

A_o/Budget Target – specification of the A_o or budget target to be achieved by the optimizing procedure.

5. System Factors. This group of data includes a variety of factors and parameters used by current Navy maintenance policies. Also included are default values for a number of item factors used by all policies. Default values,assigned by the model on the basis of the item's type, COG, cost, or MTBF are provided for the following item factors:

Procurement lead time
Order-and-ship-time
Repair cycles (by maintenance level)
Scrap rates (by maintenance level)
BCM rates (by maintenance level)
False removal rates (by maintenance level)
False removal detection rates (by maintenance level)
Expected item life
Insurance item designation

Any of the values assigned to these item factors according to the system defaults may be overridden for specific items if such information is available.

6. Run Specifications. This group of input factors establishes conditions for a given run of the model. Included are designations of maximum numbers of items, location, equipments, etc; whether or not input card images are to be listed; included program years; and run identification information which is printed in the heading of all output reports. Also included are specifications of the various features and output reports of the model which are to be included in the run.

F. CALCULATION OF MATERIAL FLOWS

In order to calculate optimal A_o COSAL levels, it is first necessary to determine rates of material flows throughout the entire support system for each defined item. These rates depend upon the definitions of the support system, parts hierarchy relationships, and a variety of system, item, and location input factors. The rates are calculated by an "expected value" model which was developed for use in LSEE. A mathematical description of this model is given in Appendix C.

As the first step of this model, "natural" failure rates are calculated for all items and operational sites (e.g., ships). This represents the amount of failures of the item that occurs at the site due to the inherent susceptibility of the item to malfunctioning resulting from operational use. The amounts are calculated upon the basis of the item's MTBF, operating factors, and number per next higher assembly for the item and all of its higher assemblies (including the ship itself).

Next, various kinds of flow rates for each item are determined according to repair processes applied to the "natural" failures. The definition and calculation of these factors can be explained by the diagram given in Figure 6-3, which shows the various operations that are possible for a given item at a given site. The process starts with the removal of the item from its next higher assembly. On the average, there will be R removals of the item per time period (quarter) which are "real" in the sense that they contain actual malfunctions; the amount R is calculated on the basis of the item's natural failure rate.

Once the amount R is calculated, an average number of false removals is determined by multiplying R by the item's false removal rate (given as an input factor). Some of the false removals are then assumed to be correctly identified as being false; this is calculated by multiplying the false removals by a false removal detection rate (also given by input data). The total removals, real plus false, less the number of detected false removals are identified as net removals which are subject to further disposition according to the LOR designation of the item.

According to the LOR designation, there are at most four possible dispositions of the net removals (identified as amount Y in Figure 6-3). Some (or all) of them may be

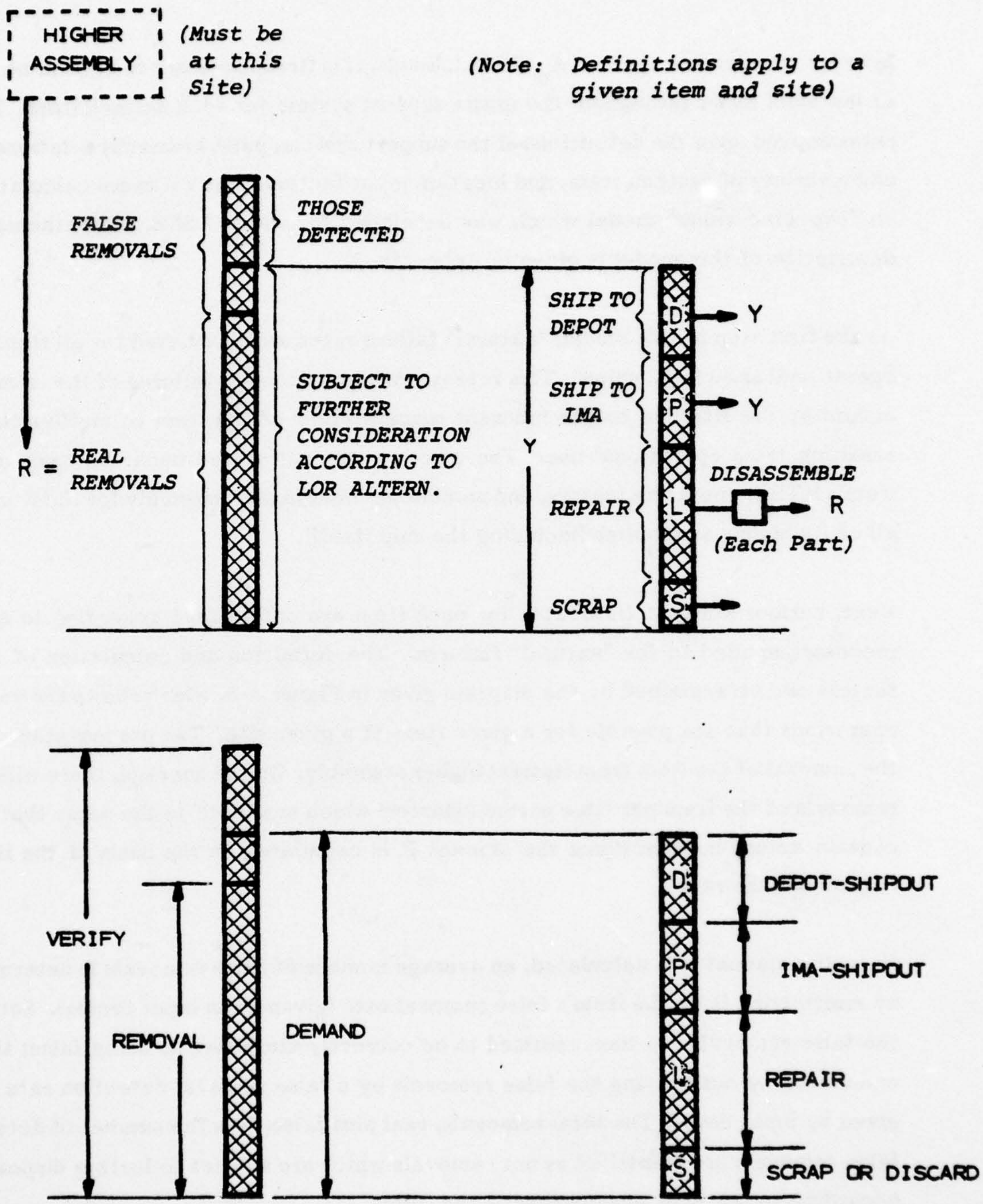


Figure 6-3. Definition of Flow Rates

scrapped or discarded (thrown away). Some (or all) may be repaired at the given site in terms of further disassembly of included parts (if any) at the next lower indenture level. Finally, some or all of the net removals may be sent to an IMA or depot for repair. The amount of net removals in each of the four disposition categories depends upon the LOR designation for the item and the type of site considered; in many instances, the amount in one or more of the categories will be zero.

If the site is an operational site and the LOR designation is organizational level repair, the "ship-outs" are first determined by multiplying net removals by the item's BCM rate. The net removals minus the ship-outs represent the amount subject to further disposition at the site. Of this amount, the number to be scrapped is determined by multiplying by a scrap rate which is a function of the item and type of site. Those not scrapped are assumed to be repaired at the site.

If the site is an operational site and the LOR designation is IMA level repair, all of the net removals are placed in the IMA and depot ship-out categories according to a split-out factor given as input. If the LOR designation is depot level repair, all of the net removals are placed only in the depot ship-out category. For both of these cases, the scrap and repair amounts at the given site are zero. Finally, for a discard LOR designation, all of the net removals are placed in the scrap category.

Amounts shipped to IMAs or depots are subject to the same disposition possibilities as the net removals, only now the given site is the relevant IMA or depot. Thus, an amount shipped to the depot is allocated to scrap or repair; there cannot be any allocation to IMA or depot ship-outs in this case. Similarly, amounts shipped to the IMA can be split out into scrap, repair or depot ship-outs at the IMA.

The amounts designated for repair at the given site are broken down into parts at the next lower indenture. For each such part, the whole pattern is repeated. Now the next higher assembly is the item previously considered, and the site is the same as before. The amount R of "real" removals for the new item is calculated as the ratio of the natural failure rate for the new item to that of the next higher assembly (the old item) times the amount of the higher assembly subject to repair at the site. A recursion is now established which provides a processing of all items down through the parts hierarchy structure of the equipment.

In the lower portion of Figure 6-3, the various annual rates calculated by the model are associated with the procedure described above. If the LOR designation calls for discard, then the discard rate shown on the right-hand side of the diagram applies (the discard rate equals the demand rate in this case); otherwise, the scrap rate applies. Thus, the scrap and discard rates are mutually exclusive for a given item and site – one or the other must always be zero.

With the above description of the processes involved, the definitions of the various rates calculated by the model can be summarized as follows:

Verify Rate. The average number of times per quarter that a malfunction (whether real or supposed) is diagnosed to exist within the given item at the given site. It is calculated as the sum of real and false removals of the given item at the given site plus the number of ship-outs received by the site from lower level repair sites. It is presumed that the fault has already been isolated to the next higher assembly of the item. Also, it is necessary that the next higher assembly be physically located at the given site or that the item has been received from some lower level repair site for further maintenance. The site(s) where the verify actions take place will depend upon LOR coding and can therefore change from one item to another.

Demand Rate. This is the expected number of demands upon the inventory of the item at the site. It is calculated as the number of verify actions minus the number of false removals identified as such as a result of the next higher assembly being physically located at the given site.

IMA Ship-out Rate. The amount shipped from the given site to IMA sites. Its calculation, as well as the other rates given below, depends upon the LOR designation and the type of the given site.

Depot Ship-out Rate. The amount shipped from the given site to depot sites for repair.

Repair Rate. The amount of the item which is inducted into the repair process at the given site. In the repair process, malfunctioning lower-level parts are removed and replaced; these will be piece parts (which are not subject to analysis or further consideration by the processes shown in Figure 6-3) if the given item is a lowest-level assembly or part.

Scrap Rate. The amount of the item which is scrapped as being uneconomically repairable. It is calculated as a percentage of the amount considered for repair at the site.

Discard Rate. The amount discarded in accordance with a discard LOR designation. It will always be zero (for other than discard policies) or equal to the demand rate.

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ANALYSIS OF SUPPLY SUPPORT IMPACTS ON EQUIPMENT OPERATIONAL AVA--ETC(U)
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The rates defined above are calculated for each item, site and quarter within a def[illegible]ed (by input data) operational program. The rates are calculated by time period (quarter) because a ship phase-in will cause them to change at the system level over time. Since system levels are calculated according to these rates and optimal COSAL levels depend upon system stocks, the optimal COSAL levels can theoretically change over time. In practice, however, the COSAL levels would probably be calculated for a particular point in the phase-in program (e.g., after the first 5 ships are operational) and then recalculated at time intervals (e.g., annually) thereafter.

G. CALCULATION OF OPTIMAL COSAL LEVELS

After the various rates defined above are calculated, they are used to calculate inventory levels for all operating sites and for the wholesale system stock. The wholesale stocks are calculated according to current Navy policies as described and defined in the LSEE User's Guide, reference (4). According to input data designations, levels at user sites are calculated by current Navy COSAL policies or by the optimizing procedure. The current COSAL policies that may be chosen include SPCC conventional, .15 FLSIP, .25 FLSIP and TRIDENT. Even though current policies are specified for some or all operating sites, the optimization procedure is still applied to these sites (as well as to sites designated for optimization) in order to produce cost/effectiveness measures.

For sites subject to optimal A_o COSAL determination, the optimizing procedure begins by calculating mean supply response times and associated equipment A_o's for all items assuming that no on-board stocks are provided. Results of this setup step give lower bounds to the operational availability of equipments – those that will occur if nothing is spent for shipboard spares.

Next, a recursive procedure is initiated. In each step of this recursion, the item and site is found for which an increase in stock level of one unit will provide the largest increase in equipment A_o per dollar. The stock level for this item and site is then increased by one unit, the mean supply response times for all affected items (the selected item and all of its higher assemblies) are recalculated, and the procedure is repeated for the next step of the recursion. This process is continued until specified A_o or budget goals are satisfied.

DATE OF RUN 10/19/77 CASE - FFG8 PRELIMINARY ANALYSIS

NAVAL SEA SYSTEMS COMMAND PMS-306
LOGISTICS SUPPORT ECONOMIC EVALUATION (LSEE)
RELEASE 5

OPTIMIZED LEVELS - END OF FISCAL YEAR 1980

INCREMENTAL FOR PRIME EQUIPMENT 1 - PUMP.PROP SWC 740GPM
OPTIMIZING CONDITIONS: COSAL LEVELS FOR USER CLASS 1 GIVEN BY OPTIMIZATION.
WHOLESALE SYSTEM STOCK GIVEN BY UICP POLICY.

ITEM NO.	DESCRIPTION	COG	UNIT COST	MTBF (HRS)	LOR	MTTR (DAYS)	SHIP MSRT (DAYS)	SHIP STOCK LEVEL	SYSTEM MSRT (DAYS)	SYSTEM STOCK LEVEL	SPENT ($1000)	CUM ASUNO
1	PUMP.PROP SWC 74	9C	3000	10498	1	.33	19.86	0	0.	0	4.16	.7312
19	SEAL-PLM ENCSD 2	9Z	1	50965	2Z	0.	.16	1	1.14	3	4.16	.7514
14	WASHER-KEY 1.009	9Z	1	78268	2Z	0.	.05	1	1.28	2	4.16	.7581
13	NUT-BRG LOCK	9Z	1	190565	2Z	0.	.04	1	.67	2	4.16	.7635
11	SEAL	9Z	17	22477	2Z	0.	1.46	1	17.43	4	4.18	.8523
18	SEAL-PLM ENCSD	9Z	1	213805	2Z	0.	.05	1	9.86	1	4.18	.8560
9	KEY.IMPELLER	9Z	2	83486	2Z	0.	.05	1	1.13	2	4.18	.8622
12	NUT-PLN RD THR	9Z	1	257824	2Z	0.	.03	1	8.20	1	4.18	.8651
15	WASHER-KWT	9Z	4	125229	2Z	0.	.13	1	16.62	1	4.19	.8732
16	BEARING-B ANN	9Z	3	109575	2Z	0.	.04	1	.66	2	4.19	.8778
17	BEARING-B ANN 1.	9Z	7	96330	2Z	0.	.04	1	.85	2	4.20	.8831
2	NUT-IMPELLER LH	1H	69	73050	2Z	0.	.40	1	27.88	1	4.27	.9019
3	NUT-IMPELLER RH	9C	69	73050	2Z	0.	.40	1	27.88	1	4.34	.9206
11	SEAL	9Z	17	22477	2Z	0.	.04	2	17.43	4	4.35	.9247
19	SEAL-PLM ENCSD 2	9Z	1	50965	2Z	0.	.00	2	1.14	3	4.35	.9249
4	RING.WEARING	9C	278	43830	2Z	0.	.59	1	13.51	2	4.63	.9660
23	CONTROLLER	1H	200	21022	2D	1.00	.03	1	1.99	1	4.83	.9787
20	MOTOR AC 25HP	1H	500	21022	2D	1.00	.03	1	1.99	1	5.33	.9914
8	COUPLING.SHAFT.F	9C	135	89449	2G	1.00	.00	1	.35	1	5.47	.9932
11	SEAL	9Z	17	22477	2Z	0.	.00	3	17.43	4	5.48	.9933
4	RING.WEARING	9C	278	43830	2Z	0.	.01	2	13.51	2	5.76	.9942
2	NUT-IMPELLER LH	1H	69	73050	2Z	0.	.00	2	27.88	1	5.83	.9944
3	NUT-IMPELLER RH	9C	69	73050	2Z	0.	.00	2	27.88	1	5.90	.9945
23	CONTROLLER	1H	200	21022	2D	1.00	.00	2	1.99	1	6.10	.9946
20	MOTOR AC 25HP	1H	500	21022	2D	1.00	.00	2	1.99	1	6.60	.9947

Figure 6-4. Incremental Generation of User COSAL

DATE OF RUN 10/19/77 CASE - FFG8 PRELIMINARY ANALYSIS

NAVAL SEA SYSTEMS COMMAND PMS-306
LOGISTICS SUPPORT ECONOMIC EVALUATION (LSEE)
RELEASE 5

OPTIMIZED LEVELS - END OF FISCAL YEAR 1980

AGGREGATED OVER ALL PRIME EQUIPMENTS.
OPTIMIZING CONDITIONS: COSAL LEVELS FOR USER CLASS I GIVEN BY OPTIMIZATION.
WHOLESALE SYSTEM STOCK GIVEN BY UICP POLICY.

ITEM NO.	DESCRIPTION	COG	UNIT COST	MTBF (HRS)	LOR	MTTR (DAYS)	SHIP MSRT (DAYS)	SHIP STOCK LEVEL	SYSTEM MSRT (DAYS)	SYSTEM STOCK LEVEL
1	PUMP,PROP SWC 74	9C	3000	10498	1	.33	3.82	0	0.	0
2	NUT-IMPELLER LH	1H	69	73050	2Z	0.	.00	2	27.88	1
3	NUT-IMPELLER RH	9C	69	73050	2Z	0.	.00	2	27.88	1
4	RING,WEARING	9C	278	43830	2Z	0.	.01	2	13.51	2
5	SHAFT,SHOULDERED	1H	665	8766003	2Z	0.	15.48	0	.48	1
6	IMPELLER,PUMP,CE	1H	1300	8766003	2Z	0.	15.22	0	.23	1
7	DEFLECTOR, DIRT	1H	36	8766003	2Z	0.	15.48	0	.48	1
8	COUPLING,SHAFT,F	9C	135	89449	2G	1.00	.00	1	.35	1
9	KEY,IMPELLER	9Z	2	83486	2Z	0.	.05	1	1.13	2
10	KEY,MACHINE	1H	2	8766003	2Z	0.	15.22	0	.23	1
11	SEAL	9Z	17	22477	2Z	0.	.00	3	17.43	4
12	NUT-PLN RD THR	9Z	1	257824	2Z	0.	.03	1	8.20	1
13	NUT-BRG LOCK	9Z	1	190565	2Z	0.	.04	1	.87	2
14	WASHER-KEY 1.009	9Z	1	78268	2Z	0.	.05	1	1.28	2
15	WASHER-KWT	9Z	4	125229	2Z	0.	.13	1	16.62	1
16	BEARING-B ANN	9Z	3	109575	2Z	0.	.04	1	.66	2
17	BEARING-B ANN 1.	9Z	7	96330	2Z	0.	.04	1	.85	2
18	SEAL-PLM ENCSD	9Z	1	213805	2Z	0.	.05	1	9.86	1
19	SEAL-PLM ENCSD 2	9Z	1	50965	2Z	0.	.00	2	1.14	3
20	MOTOR AC 25HP	1H	500	21022	2D	1.00	.00	2	1.99	1
21	BEARING-B ANN 1.	1N	57	93255	DZ	0.	0.	0	3.61	2
22	BEARING-B ANN 2.	1N	71	32467	DZ	0.	0.	0	23.63	2
23	CONTROLLER	1H	200	21022	2D	1.00	.00	2	1.99	1
24	FUSE-CART	9N	1	18533	DZ	0.	0.	0	3.52	7
25	METER	9G	75	730500	GG	.50	0.	0	.06	1
26	CONTACT-ELECT	9N	2	302276	DZ	0.	0.	0	.41	3
27	CONTACT-ELECT	9N	1	974000	DZ	0.	0.	0	8.93	1
28	CONTACT-ELECT	9N	4	417429	DZ	0.	0.	0	6.21	2
29	CONTACT-ELECT	9N	4	398455	DZ	0.	0.	0	1.85	2
30	TRANSFORMER	1N	45	584400	DZ	0.	0.	0	7.46	1
31	SPRING-MLCPS	9Z	1	547875	DZ	0.	0.	0	15.67	1
32	SPRING-MLCL	9Z	1	199227	DZ	0.	0.	0	.59	3
33	SWITCH-RTY	9G	43	365250	DZ	0.	0.	0	11.84	1
34	COIL-RLY	9N	35	153790	DZ	0.	0.	0	1.39	2

Figure 6-5. Summary of Final Stock Levels

The optimizing model and solution procedure are described in mathematical terms in Appendix B. The various rates calculated as described in the previous section are essential inputs to the optimizing procedure. As the procedure operates and specified A_o or budget goals are attained, results in terms of COSAL levels and associated MSRTs and A_o measures are determined and presented in output reports.

H. OUTPUT REPORTS

Results of the optimizing procedure are presented in two output reports, each having the same general format. In the heading of the reports, the designated optimization conditions are given. The first report gives results of each step of the recursive procedure described above. For each step, it identifies the site and item selected for stock augmentation, the new stock level and associated MSRT, and the cumulative expenditure and attained equipment A_o at that step.

The second report is produced at the end of the recursive procedure after the target A_o or budget goals have been achieved. Items are listed in sequence and the final stock levels and MSRTs are given. In both reports, various item factors are given for reference, including the item description, cog, unit cost, and MTBF. Examples of the two output reports are given in Figures 6-4 and 6-5.

Data in the first output report (Figure 6-4) may be used to construct cost/effectiveness curves. The equipment operational availability, A_o, attained at each step of the recursive procedure (corresponding to a line entry on the report) is plotted against the total amount spent for spares at that point of the procedure. The result is a curve similar to that illustrated in Figure 6-6.

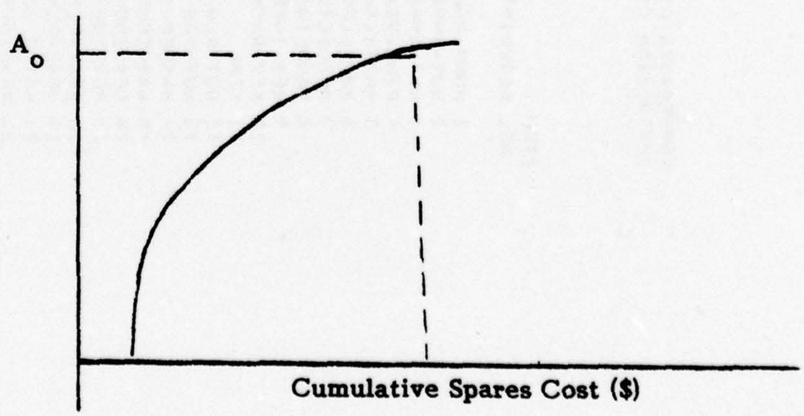

Figure 6-6. Example Cost/Effectiveness Curve

The cost/effectiveness curve represents the maximum A_o that can be obtained for any given level of expenditure for spares. Points lying below the curve represent less efficient policies since the optimal policy can give the same A_o at less cost or a greater A_o at the same cost. The optimizing procedure of the model permits the calculation of points for current Navy policies for purposes of comparison. These are shown and discussed in the next section for two example equipments.

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VII. ALTERNATIVE COSAL METHODOLOGY: ANALYSIS RESULTS

A. DESCRIPTION OF EQUIPMENTS

Two items of shipboard equipment were used to test the optimal A_o COSAL model and demonstrate its operation. They are:

- A Sea Water Circulating Pump
- AN/UYK-7 Computer

The sea water pump consists of a pump, an electric drive motor, and an interconnecting coupling. An engineering drawing of the pump is shown in Figure 7-1 together with a schematic of its parts breakdown as considered by the model.

The motor and motor control are identified as major assemblies within the pump unit. They are broken down further into discard items (indicated by circles in the diagram given in Figure 7-1) except for one item in the control which is reparable at the IMA level. Parts within the pump and coupling are identified as consumable items except for one assembly which is reparable at the IMA level.

The parts breakdown given in Figure 7-1 and represented by data that is input to the model does not include all parts needed in the supply system to repair and maintain the pump unit. Excluded, in particular, are many parts used in depot level repair and overhaul. Essentially, the parts candidate list for the case study was drawn from the APL (Allowance Parts List) for the pump, which generally excludes items needed for higher-level maintenance.

The AN/UYK-7 computer is contained in two small cabinets as shown in Figure 7-2. The computer consists of five major functional components as indicated in the schematic of its parts breakdown also given in Figure 7-2. These components can be removed and replaced, and hence are considered as candidates for stockage aboard the ship.

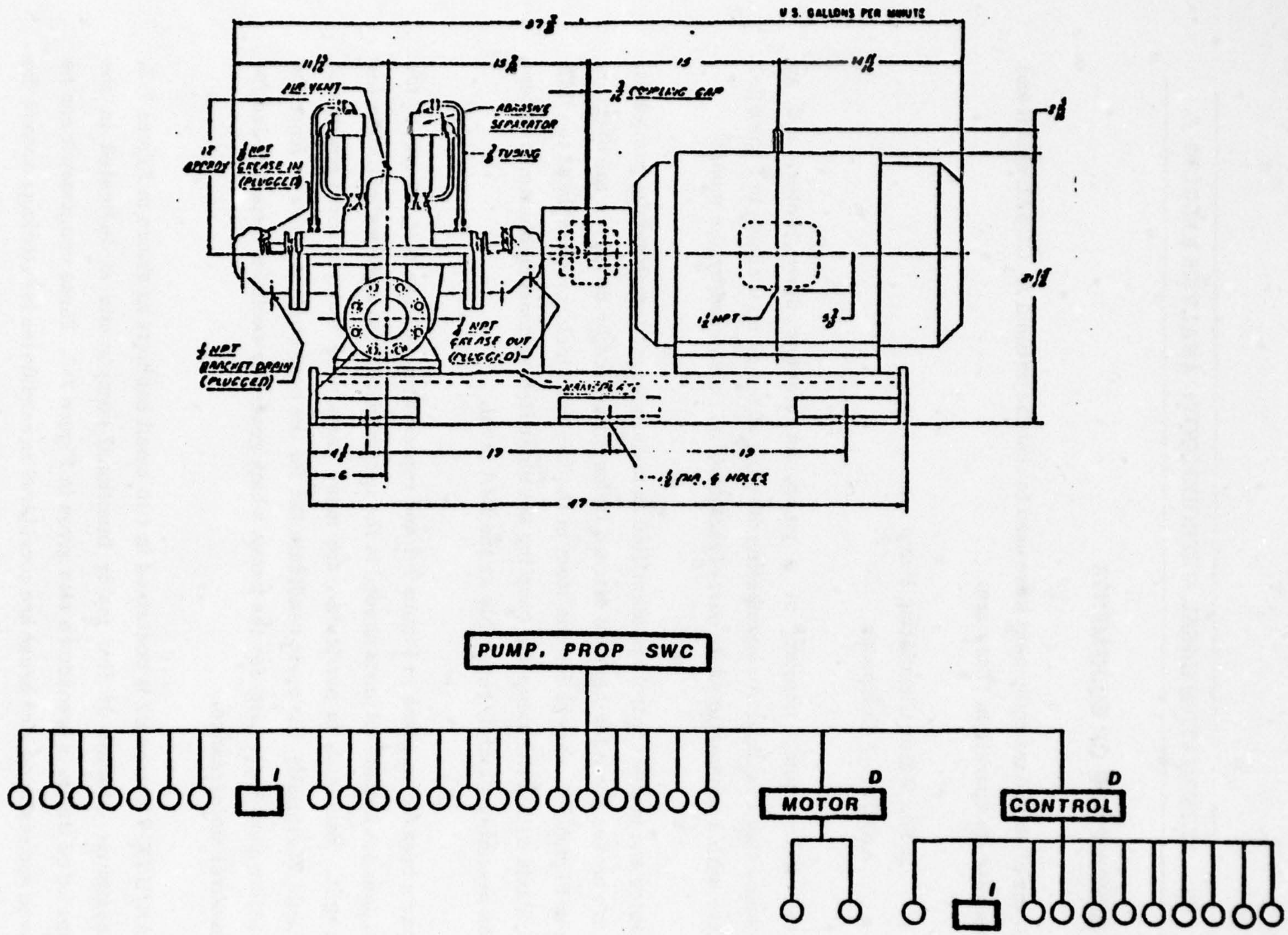

Figure 7-1. Example 1 - Seawater Pump

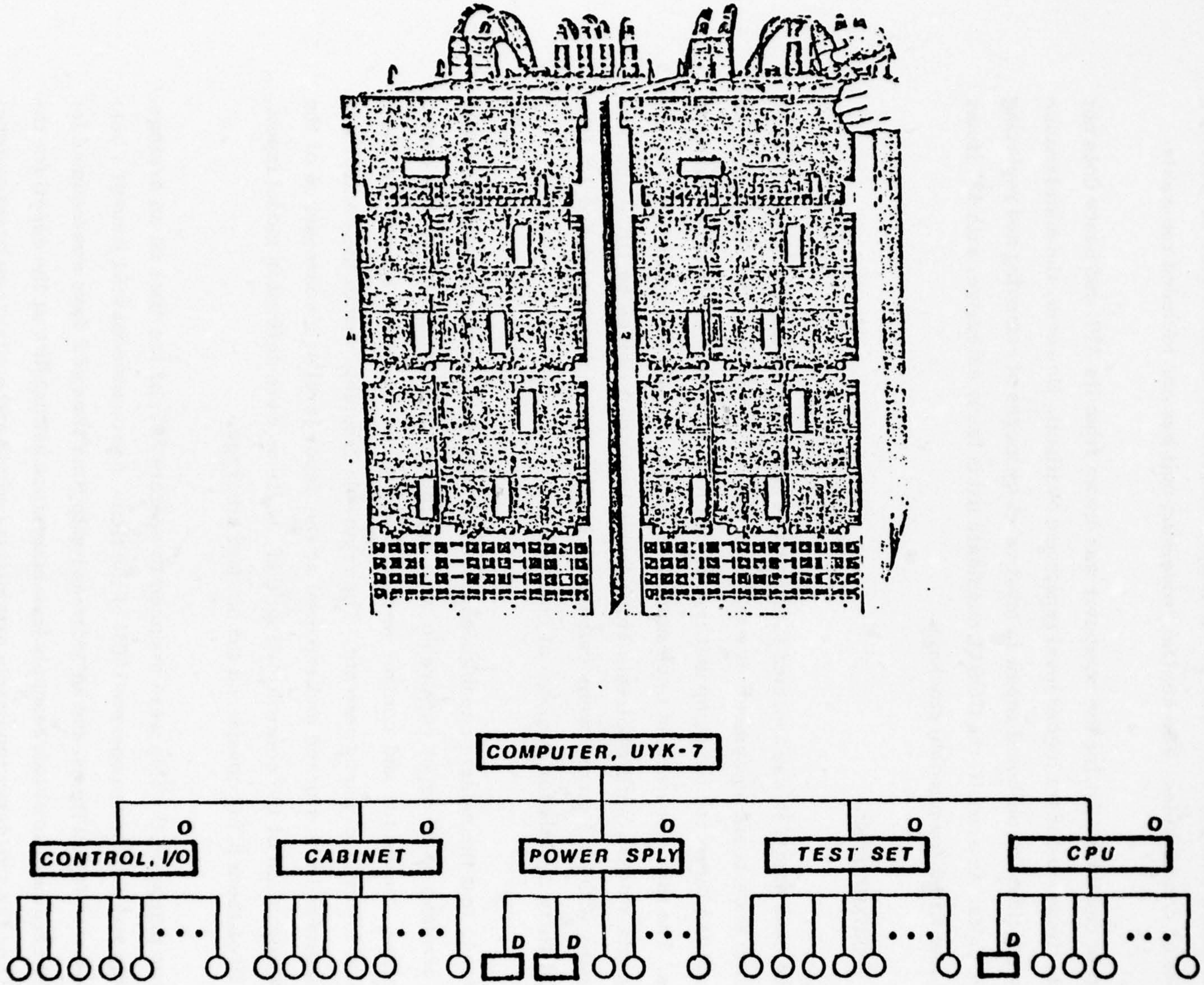

Figure 7-2. Example 2 - AN/UYK-7 Computer

Each component of the computer is further broken down into a number of consumable parts (indicated by circles in the parts breakdown schematic), most of which are plug-in electronic components. The power supply has two reparable items as well as a number of consumables. The central processing unit has one included reparable.

The item candidate list for the computer was drawn from its APL and hence does not include items needed for higher level repair and overhaul. However, the maintenance policy provides for on-board repair in most cases by means of removing and replacing plug-in units. As a result, the COSAL candidate list is fairly extensive, with 483 items being identified for possible stockage.

B. ASSUMPTIONS

For the case study, it was assumed that only one ship is operational with two units of the pump as on-board equipment. It was assumed that all repairs of the pump are done in-place and therefore the pump unit itself is not a candidate for on-board stockage as spares. The ship was assumed to be supported by depot-level maintenance and supply (wholesale stocks), with wholesale stock levels being determined by UICP policies. Shipboard (COSAL) stocks were calculated by the optimizing model and by four current Navy models for purposes of comparison.

In order to test the model's capabilities more thoroughly, the motor and motor control were assumed to be depot repairable with all failed units being sent to the depot. Therefore, the motor and control were considered for on-board spares, but their included lower level parts were not. The reparable assembly within the control was also assumed to be stocked and repaired at the depot level as a consequence of the LOR designation of the control. Altogether, 34 items were defined in model inputs, with 20 of them being considered for on-oard stockage.

The two pumps on the ship were assumed to operate 80% of the time on an average. The ship was assumed to operate 100% of the time. A procurement lead time of 1 year was assumed for all items, and an order-and-ship time time of 8 days was assumed for the time required to obtain resupply (assuming stock availability at the depot) for the ship. For the two depot repairable assemblies (motor and control), an average depot

and control), an average depot repair cycle of 30 days was assumed. A mean-time-to-repair (MTTR) for the pump upon failure was assumed to be 8 hours regardless of which item caused the failure.

Unit procurement costs of items included in the pump analysis ranged from $1 for lower-level consumable items to $500 for the motor. The highest cost items were two consumables in the pump, an impeller at $1300 and a shaft at $665. The estimated annual failure rates (BRF) for included items ranged from .835 for the pump unit itself to .001 for several of the included consumables.

Several cogs were represented by parts of the pump, including 1H, 9C, 9N, 9G, and 9Z. All parts were assigned a (TRIDENT) MEC code of 98 or "vital" according to conventional SPCC essentiality coding.

A variety of assumptions were made concerning the parameters used by the UICP wholesale stock policy. In general, these conformed to values currently used by the UICP system.

The demand process was assumed to be Poisson for means of 1 or less and negative binomial for higher means. The variance of the negative binomial distribution was calculated as a function of the mean according to a formula and parameters currently used in the UICP system.

For the analysis of the computer it was assumed, as in the pump example, that only one ship is operational and that the computer is repaired in-place so that the computer itself is not a candidate for stockage as spares. It was assumed that there is one unit of the computer aboard the ship and that it operates 80% of the time the ship operates. Since the ship was also assumed to operate 80% of the time, the net operating time for the computer is 64%. The ship was assumed to be supported by depot level maintenance and supply, with system stock being given by UICP policies. Shipboard stocks were calculated by the optimal COSAL model and by the four current Navy policies for comparison.

All five major components of the computer were assumed to be reparable at the organizational level The reparable assemblies within the power supply and CPU were assigned LOR codes for depot repair. All other parts were coded as consumables. All parts of the computer, as indicated in Figure 7-2, were considered as candidates for COSAL stockage

A procurement lead time of 1 year was assumed for all items and the order-and-ship time was set to 8 days. A 30 day depot repair cycle was assumed for the 3 depot repairable assemblies. A mean time to repair of 2.4 hours was assumed for the computer regardless of which item caused the failure. For demonstration purposes all items were assigned a (TRIDENT) MEC code of 95 which is equivalent to the "nonvital" SPCC essentiality code. This is the lowest essentiality in the TRIDENT program.

Parameters for the UICP stockage policy and types of demand distributions were assigned according to current UICP usage; these were the same as for the pump case.

C. ANALYSIS RESULTS

Five runs of the model were made with the pump data, and for each of the following COSAL policies:

- A_o Optimization
- SPCC Conventional
- .15 FLSIP
- .25 FLSIP
- TRIDENT

For all five runs, system stock levels were calculated according to UICP policies. For the optimal A_o COSAL run, the achieved equipment A_o as a function of investment in spares was obtained. For the other four runs, where COSAL levels were given as well as system stocks, the equipment A_o's achieved by the indicated investments were calculated. Results of the runs in terms of A_o as a function of investment in spares are given in the following table; this data is also plotted in Figure 7-3:

Optimal COSAL A_o	$K	SPCC Conv. A_o	$K	.15 FLSIP A_o	$K	.25 FLSIP A_o	$K	TRIDENT A_o	$K
.7309	4.08	.9896	7.38	.9687	5.36	.9088	5.08	.9857	5.26
.7490	4.09								
.8246	4.10								
.8432	4.11								
.8499	4.12								
.8730	4.19								
.8961	4.26								
.9460	4.54								
.9677	4.76								
.9885	5.26								
.9937	5.67								
.9940	5.76								
.9944	6.02								
.9947	6.52								

The number of items stocked in the COSAL for the five policies are shown in the following table, where the data for the optimal policy represents the stockage range at the end of the procedure:

	Optimal	SPCC Conv.	.15 FLSIP	.25 FLSIP	TRIDENT
# of items stocked	20	20	10	6	14
% of full range	100	100	50	30	70

Computer time required for the optimal COSAL model was approximately 1.10 CPU seconds. Core requirements were about 245K bytes, with about 230K being required for the model itself (which included the entire LSEE model as well as the optimizing routines). The remainder, about 15K, was used for input data and results of the computation.

For the analysis of the computer, five runs were made, as in the pump case. The runs were according to type of COSAL policy, with UICP policies being used to calculate system stocks. Results in terms of equipment A_o's as functions of investment are given in the following table and plotted in Figure 7-4:

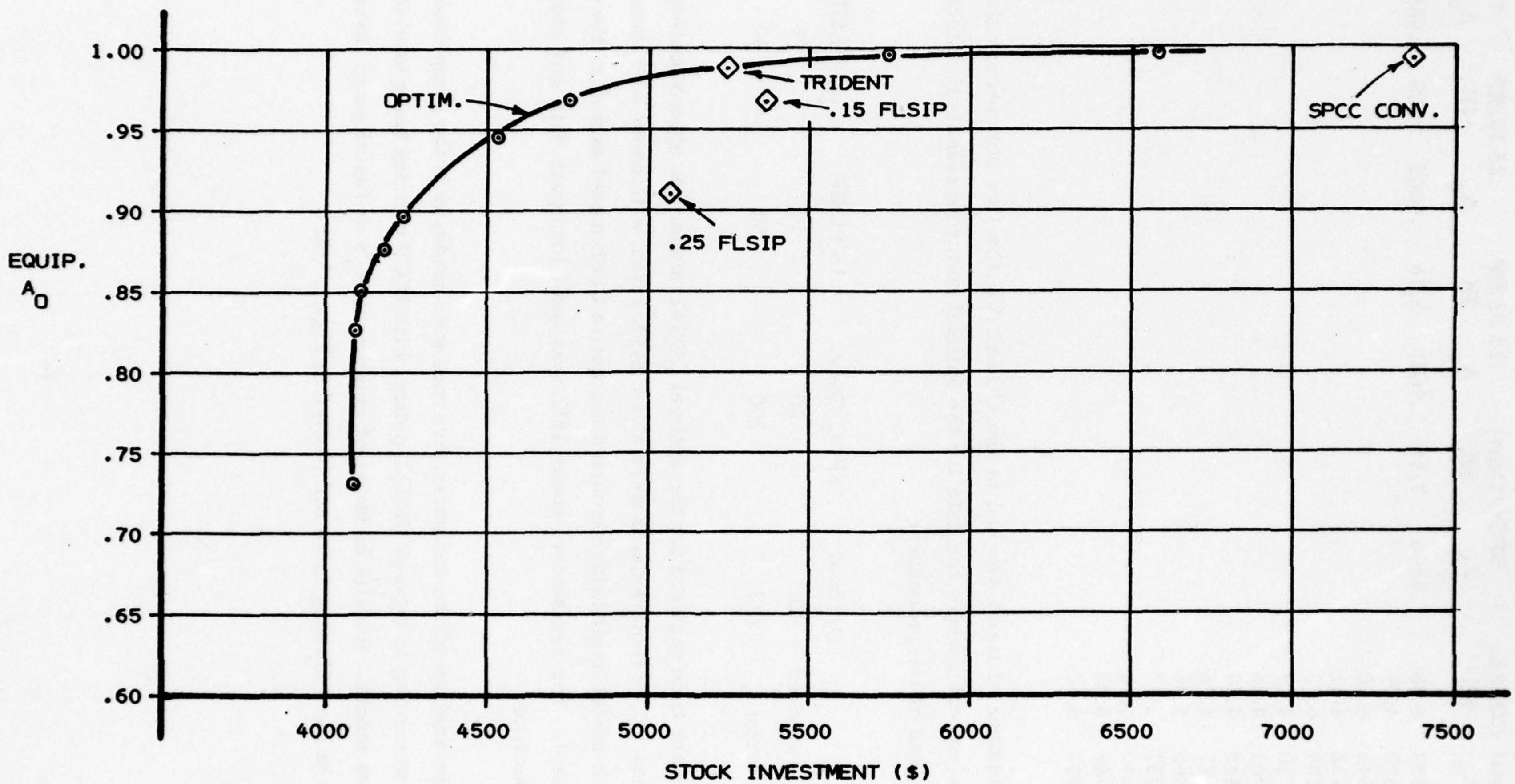

Figure 7-3. Cost-Effectiveness Results for the Pump Example

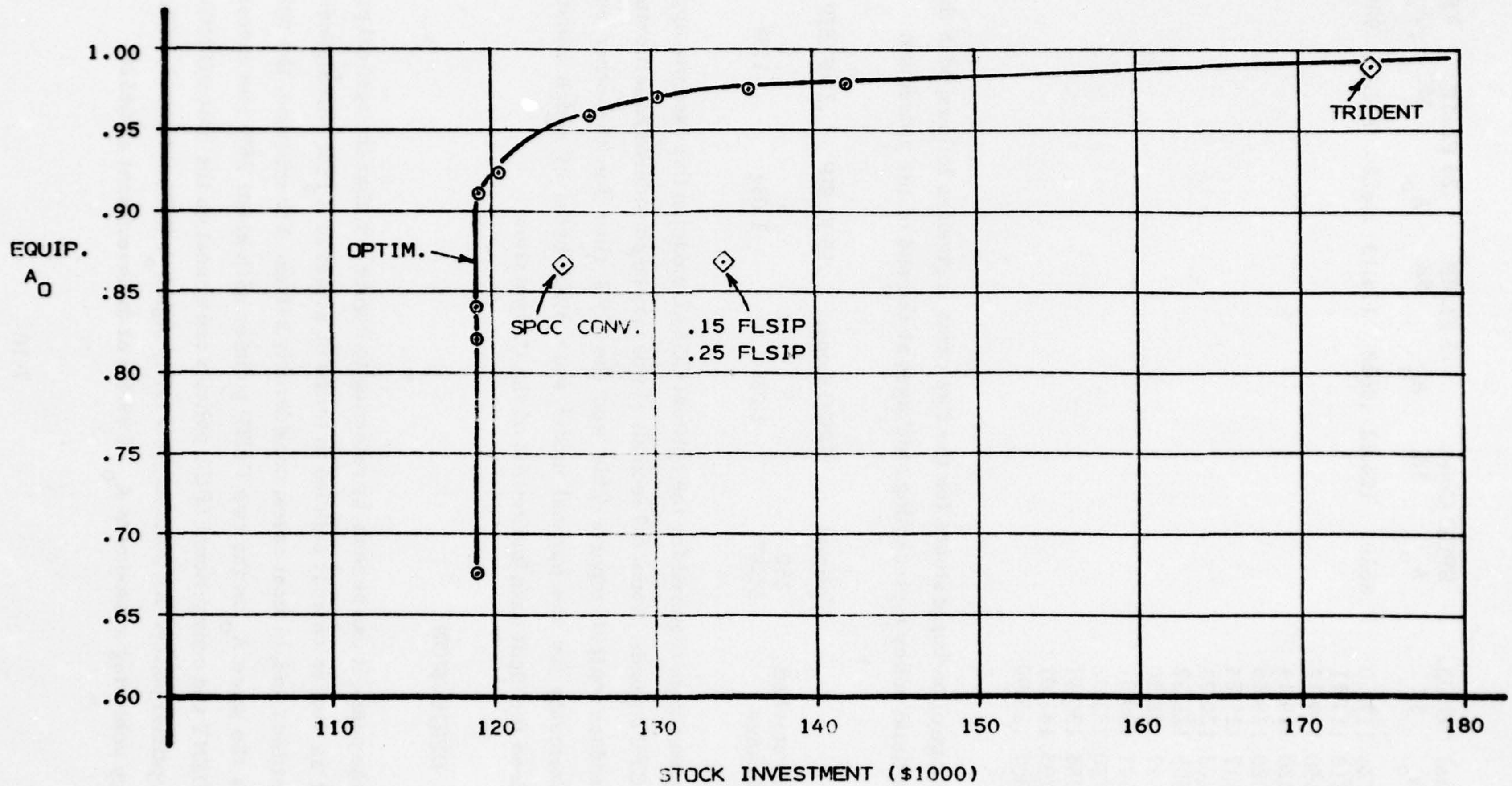

Figure 7-4. Cost-Effectiveness Results for the Computer Example

Optimal COSAL A_o	$K	SPCC Conv. A_o	$K	.15 FLSIP A_o	$K	.25 FLSIP A_o	$K	TRIDENT A_o	$K
.6724	119.10	.8620	124.12	.8628	134.13	.8628	134.13	.9892	174.58
.8218	119.11								
.8350	119.12								
.8420	119.14								
.9020	119.54								
.9117	119.84								
.9212	120.74								
.9588	126.32								
.9657	128.30								
.9691	130.31								
.9730	133.32								
.9754	135.91								
.9793	142.01								
.9967	186.90								

The range of on-board stocks for the five cases is given as follows, with the range for the optimal policy representing stockages at the end of the procedure:

	Optimal	SPCC Conv.	.15 FLSIP	.25 FLSIP	TRIDENT
# of items stocked	250	5	5	5	58
% of full range	51.87	1.03	1.03	1.03	12.03

Computer time required for the optimal COSAL model in this case was approximately 9.55 CPU seconds. About 6.9 seconds of this may be considered as setup time and time to produce output reports (this was the CPU time for the other runs). Core requirements for the optimal model were 398K bytes of which about 168K was required for input data and results of the computation.

D. DISCUSSION

For the pump, it can be seen, by referring to Figure 7-3, that the optimal policy does at least as well as current policies in terms of achieved A_o for corresponding levels of investment and, in most cases, considerably better. For example, the optimal policy gives the same A_o as the two FLSIP policies with about 25% less investment. The TRIDENT and conventional SPCC policies are almost on the cost-effective curve for the optimal policy. All policies yield fairly high A_o's (90% or better), with the optimal policy achieving a maximum A_o of 99.4% at an investment of $6520.

The results for the pump are dominated by two main characteristics of the input data. First, the failure rate of the pump is fairly low - a failure occurs about once per quarter. Since the pump is out of commision 8 hours per failure due to non-supply related causes (e.g., MTTR), the maximum achievable A_o (assuming infinite on-board spares) is 99.48%. Thus high A_o rates can be achieved with fairly modest investments in spares.

Second, runs made with "nonvital" item essentiality assignments produced zero levels for all items for the SPCC conventional and FLSIP policies due to low demand rates. Therefore, to obtain useful policy comparisons, all items were assigned "vital" essentiality factors (TRIDENT MEC codes of 98) for this study. For the conventional SPCC policy, this caused all items to be stocked with 1 unit each which accounts for the high A_o and high investment. These essentiality codes also caused the TRIDENT policy (which, in general, provides "liberal" stocks in terms of both range and depth) to lie very close to the optimal A_o for the corresponding level of investment. The two FLSIP policies, which are not sensitive to unit costs of the items, did not perform as well; the .15 FLSIP performs better because of its higher range.

Results of the runs are also largely influenced by system stocks established by UICP policies. It may be noted that an A_o of 73% is achieved with no on-board stocks because of the $4080 investment in system spares. An additional $1000 for on-board spares raises the A_o to about 98% according to the optimal policy. Actually, the first $200 spent raises the A_o to almost 90% because of the inexpensive items which are selected first for stockage.

It may be concluded from these results that an investment of about $1300 in on-board spares according to the optimal policy, yielding an A_o of about 99%, is desirable for the pump. Coincidently, the TRIDENT policy yields nearly the same results for this case, with a slightly different mix of range and depth.

For the computer, it may be seen by referring to Figure 7-4 that the optimal policy gives higher A_o's than the current policies for the same investment. The SPCC conventional policy gives about the same A_o as the two FLSIP policies (which gave identical results) but with less investment. The TRIDENT policy is a very expensive one, but it yields a high A_o which is nearly on the optimal curve.

As in the pump case, the failure rates of the computer and included parts are relatively low, with the computer failing about once a month on the average. This yields high A_o rates as stockage increases since the computer is down for non-supply reasons about 2.5 hours per month.

Since all items were assigned "nonvital" essentiality codes, the SPCC conventional and the two FLSIP policies stocked only a few of the higher demand items without regard to their cost. However, the few items stocked raised the A_o for 67% for no stockage to about 87%. On the other hand, the optimal policy achieves 95% or better A_o for the same investment.

The UICP policy caused an initial investment of $119,000. The optimal policy immediately raised A_o to over 90% by spending a few hundred dollars on a range of inexpensive parts for on-board spares. After that, marginal increases in A_o were achieved at larger marginal increases in investment due to stockage of more expensive spares.

An investment of about $12,000 for on-board spares (about 10% of the system stock investment) will yield an A_o of about 97% if the optimal policy is followed. The TRIDENT policy spends about 4 times as much to raise A_o another 2%. If a point on the optimal cost-effectiveness curve is chosen at the 97-98% level, the optimal policy gives a much higher A_o than the FLSIP policies at about the same investment, and about the same A_o as the TRIDENT policy at about 25% of the investment.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. INTRODUCTION

The conclusions and recommendations which were obtained as a result of this analysis are aggregated by the three main areas of study:

- Evaluation of methodology to obtain values of reliability, maintainability, and supply response
- A_o parametric analysis
- Alternative COSAL methodology

B. DETERMINING VALUES OF MTBF, MTTR AND MSRT

Based on an analysis of the determination of benchmark values for reliability, maintainability and supply response, several conclusions were reached regarding the availability of relevant data. They are:

- The CASREP system and the 3-M system did not include sufficient data on two originally selected equipments to allow an analysis to be made.
- Inconsistencies exist in the processing of CASREP which are not corrected prior to a ship's overhaul.
- For A_o analysis, population statistics would be improved if it were possible to determine the birth date of each member of all APL groups.
- Failure to identify the supply source in CASREP and 3-M reporting precludes direct calculation of MSRT. Several recommendations for corrective actions are provided in Section III.

C. A_o PARAMETRIC ANALYSIS

Based upon ASUBO ANALYZER program development and the results of program testing with the two electronics equipments, several conclusions have been reached concerning the program and future development. These conclusions and recommendations for continued work are presented below.

1. Conclusions

The main conclusions obtained from program development and testing are as follows:

- The ASUBO ANALYZER operates as designed. Within the specified assumptions and constraints, the program calculates A_o as a function of reliability, maintainability, and supply response time.

- For a given equipment type the impact of improved or degraded reliability, maintainability, and supply response may be measured and compared.

- The impact on A_o of changes in repair time or response time at a specific level of maintenance or supply may be determined by using the program.

- For the two equipments tested, the impacts on A_o of maintainability and supply response were about equal and significantly greater than the reliability impact.

- The model may be modified to determine the least-cost allocation of funds to a mix of reliability, maintainability, and supply response improvements.

2. Recommendations

- An extensive effort should be made to estimate the cost of several levels of reliability, maintainability, and supply response. A set of non-continuous cost functions will be the product of this effort.

- The model should be modified to accommodate reliability, maintainability, and supply response cost functions and generate an optimum solution to the resource allocation problem.

- An implementation plan should be developed whereby the Navy can take advantage of information about optimum allocation of funds to improve reliability, maintainability, and supply response.

D. ALTERNATIVE COSAL METHODOLOGY

Based upon the model development accomplished so far and limited results from two case studies several conclusions have been reached concerning the current model and its future development. These conclusions and recommendations for future work are presented below.

1. Conclusions

The main conclusions obtained from model development and case studies accomplished to date are as follows:

- The optimal A_o COSAL model operates as designed. Within specified assumptions and constraints, it calculates COSAL levels for given equipments which maximize the equipment A_o for a given spares budget or minimizes the budget required to achieve given A_o targets.

- The model provides a way to measure the A_o impact of any set of shipboard stocks including those given by current Navy policies.

- The model provides a way for determining tradeoffs between expenditures for spares and operational availability of equipments. This is provided by cost/effectiveness curves derived from model outputs.

- Optimal stockages produced by the model are more cost-effective than those of current Navy COSAL models.

- The structure of the model and its solution procedure enables (as a later development) the satisfaction of various additional constraints such as storage space or number of items stocked. Impacts of such constraints upon equipment A_o can be measured.

- Computer resource requirements and CPU times for the model are reasonable and practical.

- Data requirements for the model are generally available in Navy management systems. An area of potential difficulty, however, is the identification of parts in terms of parts breakdown relationships and the corresponding development of candidate lists for stockage at not only ship level but also system level.

- The two case studies included in the report are extremely limited in scope and cannot serve as a basis for any kind of extrapolation concerning model operation and potential benefits. At best, they serve to demonstrate the operation of the model and its possible benefits.

2. Recommendations

Based upon the above conclusions, several recommendations are made concerning continued model development, test, and planning for implementation. Principal recommendations are as follows:

- It is recommended that model development be continued to overcome current limitations and assumptions and to add new features and capabilities. Additional model development is indicated in the following areas:

  The model currently assumes one-for-one ordering at all supply levels. This should be revised to permit batch ordering and the calculation of economic ordering quantities at selected locations or supply echelons.

  The model currently assumes that failures of parts within an equipment are independent and that an equipment failure is due to only one part at a time. The model should be revised to permit representation of failure dependencies and multiple failure occurrences of parts.

Expected number of failures per unit time are currently assumed to be independent of A_o and remain the same regardless of how long the equipment is inoperable due to lack of spares. This assumption should be removed by making failure rates dependent upon achieved A_o.

Two echelons of supply, user and system, are currently represented in the model. The model should be extended to consider (at least) 3 echelons to account for additive stockages aboard tenders and supply ships, at certain IMA sites, for prepositioned war reserve requirements, etc.

The model should be extended to permit the input of existing stockages at selected sites and to account for such stocks in establishing optimal levels and measuring equipment A_o.

Current methods for calculating material flow rates based upon LOR codes and for converting SM&R codes to LOR codes should be revised as discussed in Section VI.

The model should be revised to permit calculation of endurance levels in situations where resupply is unavailable for given time periods. Currently, the model assumes continuous resupply opportunity.

The model should be extended to consider a variety of additional constraints and conditions that are necessary for operational use of the model. Included are constraints imposed by storage space limitations, the number of items subject to supply management aboard a ship, minimum replacement units, insurance items, special source and disposition conditions, etc.

Methods should be developed to calculate levels in context with incremental provisioning and to revise levels as additional appearances of common items occur.

Output formats of the model should be revised to present results in more usable forms. Special outputs should be provided to facilitate the analyses recommended below.

- It is recommended that an analysis program be conducted to further investigate the properties and behavior of the optimal A_o COSAL model. This effort, overlapping the model development program recommended above, would include the following:

A database should be constructed for use in the analysis. Included should be data for equipments of several sizes and types which are representative of the variety and special characteristics of operational equipments.

Case studies on the selected equipments should be conducted under a variety of assumptions concerning the equipments' operational and

support environment. Results should be evaluated and compared with particular emphasis upon identifying sources of model deficiencies and needed corrective actions.

Sensitivity analyses within and across equipments should be conducted to identify types of data upon which results are most dependent and to quantify impacts upon operational availability of equipments.

Based upon results of the case studies and analyses, projections should be made of potential costs and benefits that would accrue upon full implementation of the model.

- Assuming that the above model development and analysis effort indicates full-scale implementation of the model is warranted, a detailed and comprehensive plan for the implementation should be developed. Particular attention should be placed upon the roles and interrelationships of activities involved in the implementation and the overall management of the implementation effort. The plan should contain estimates of time and personnel requirements for implementation of the model and associated data systems.

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(3) Prichard, J. W., Preliminary Design and Data Sources for Parametric Analysis of Operational Availability, Center for Naval Analyses Memorandum, 27 June 1975

(4) Logistic Support Economic Evaluation User's Guide, Release 4, Naval Weapons Engineering Support Activity, Washington, D. C., November, 1976.

APPENDIX A

ASUBO ANALYZER

APPENDIX A: ASUBO ANALYZER

CONTENTS

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I. INTRODUCTION

A Center for Naval Analyses Memorandum of 27 June 1975 describes a preliminary design for a computer program to be used to assess the impact of several factors on operational availability, A_o. A program called ASUBO ANALYZER has been developed to provide the capability for such analyses. The mathematical description of the program, input data requirements, and output statistics are described herein.

II. MATHEMATICAL DESCRIPTION

Define operational availability, A_o, of an item of equipment or system as follows:

(1) $A_o = R/(R+M+Q_1PS)$

where,

R = Mean time between equipment or system failures which require corrective maintenance action (days)

M = Mean time to repair the equipment or system including time in transportation and awaiting parts and personnel if the equipment or system is repaired off ship (days)

S = Mean time to supply parts to the ship given that the maintenance action requires one or more repair parts and the repair is done at the shipboard level (days)

Q_1 = Probability that the repair is done at the shipboard level by the ship's crew

P = Probability that the repair action requires one or more parts

The first derivatives of A_o with respect to R, M, and S are as follows:

$$\delta A_o/\delta R = (M+Q_1PS)/(R+M+Q_1PS)^2$$

$$\delta A_o/\delta S = -(Q_1PR)/(R+M+Q_1PS)^2$$

$$\delta A_o/\delta M = -R/(R+M+Q_1PS)^2$$

Mean time between equipment or system failures, R, is assumed to be elapsed time in days. It is calculated from two input variables as follows:

(2) R = RZ/F

where,

RZ = operating time between failures expressed in days

F = an operating factor representing the ratio of equipment operating time to elapsed time

Mean time to repair the equipment or system, M, is measured in elapsed time in days. It is calculated as follows:

(3) $M = Q_1L_1 + (1-Q_1)(Q_2L_2+Q_3L_3+Q_4L_4)$

where,

Q_1 = Probability of repair at the ship by ship's crew

Q_2 = Probability of repair at the ship with technical assistance

Q_3 = Probability of repair at a shipyard or tender

Q_4 = Probability of repair in overhaul or drydock

L_1 = Time to repair at the ship by ship's crew (days)

L_2 = Time to repair at the ship with technical assistance (days)

L_3 = Time to repair at a shipyard or tender (days)

L_4 = Time to repair in overhaul or drydock (days)

and,

$Q_2+Q_3+Q_4 = 1.0$

Mean time to supply parts to the ship, S, is measured in elapsed time in days. It is calculated as follows:

(4) $$\begin{aligned} S = {} & B_1T_1 + (1-B_1)B_2T_2 + \\ & (1-B_1)(1-B_2)B_3T_3 + \\ & (1-B_1)(1-B_2)(1-B_3)B_4T_4 + \\ & (1-B_1)(1-B_2)(1-B_3)(1-B_4)B_5T_5 \end{aligned}$$

where,

B_1 = Probability of supply by the ship

B_2 = Probability of supply by Mobile Logistic Support Force (AFS)

B_3 = Probability of supply by point of entry (stock point)

B_4 = Probability of supply by the wholesale system (ICP)

B_5 = Probability of supply by vendor (B_5=1.0)

T_1 = Time to supply by the ship (days)

T_2 = Time to supply by Mobile Logistic Support Force (days)

T_3 = Time to supply by point of entry (days)

T_4 = Time to supply by the wholesale system (days)

T_5 = Time to supply by the vendor (days)

The supply probabilities $B_1 \ldots B_5$ are to be interpreted as the probability of supply from that echelon given that there is a demand for a part placed on the system at that level. It is assumed that the part can always be obtained from a vendor (B_5=1.0).

For a given equipment or system the program calculates initial values of R, M and S from input values and equations (2), (3) and (4). An initial value of A_o is calculated from (1). From these initial values several parametric analyses are conducted. Tabular results and plots are provided. The analyses are as follows:

- Mean time between corrective maintenance actions, R, is varied over a range selected by the user. M and S are held at their initial values. For each value of R; A_o, $\delta A_o/\delta R$, $\delta A_o/\delta M$, and $\delta A_o/\delta S$ are calculated.
- Mean time to repair, M, is varied over a range selected by the user. R and S are held at their initial values. For each value of M; A_o, $\delta A_o/\delta R$, $\delta A_o/\delta M$ and $\delta A_o/\delta S$ are calculated.
- Mean time to supply parts to the ship, S, is varied over a range selected by the user. R and M are held at their initial values. For each value of S; A_o, $\delta A_o/\delta R$, $\delta A_o/\delta M$ and $\delta A_o/\delta S$ are calculated.
- For each of ten values of A_o selected by the user, the production functions R versus M, R versus S, and S versus M are determined. The third variable, in each case, is held to its initial value.
- The ratios of partial derivatives are calculated as a function of A_o.

III. INPUT DATA REQUIREMENTS

Tables A-1 through A-4 provide the format and data element descriptions for each input data element. Each table lists the information for one input record (card) type. The order of the input data cards is as follows:

1. Card Type 1, one only
2. Card Type 2, one only
3. Card Type 3, one or more for each of five sets of factors used to generate a range for variables. The ordering of these card types is:
   - Factors FX01(I) are for the first report, A_o versus MTBCMA
   - Factors FX02(I) are for the second report, A_o versus MTTR
   - Factors FX03(I) are for the third report, A_o versus MSRT
   - Factors FX04(I) are for the set of production function reports
   - Factors FX05(I) are for the report on the ratio of partial derivatives
4. Card Type "B", one for each equipment for which an analysis will be conducted
5. One "End" card to signal the end of input data. ("E" in column 1)

The format coding used in Tables A-1 through A-4 are interpreted as follows:

I n - Integer, right justified in field of n characters

A n - Alphanumeric, right justified in field of n character

D(m,n) - Decimal number, total number of characters, including the decimal point, is m. There are n characters to the right of the decimal point.

TABLE A-1. Card Type 1, Data Elements and Formats

Data Element	Card Columns	Format
Report Switch 1 - If switch is set to 1, the first report, A_o versus MTBCMA, is printed.	1	I 1
Report Switch 2 - If switch is set to 1, the second report, A_o versus MTTR, is printed.	2	I 1
Report Switch 3 - If switch is set to 1, the third report, A_o versus MSRT, is printed.	3	I 1
Report Switch 4 - If switch is set to 1, the production function reports; MTBCMA versus MTTR, MTBCMA versus MSRT, and MSRT versus MTTR are printed.	4	I 1
Report Switch 5 - If switch is set to 1, the report on the ratio of partial derivatives is printed.	5	I 1
Ten values of A_o selected by the user. These values are used in determination of the production functions.	6-35	D(3,2)

TABLE A-2 Card Type 2, Costs and Cost Factors

Data Element			Card Columns	Format
SCOST	-	Cost to supply the parts required for each maintenance action corrected on the ship by ship's personnel ($).	*	*
MCOST	-	Cost to repair the equipment, averaged over all maintenance levels ($).	*	*
RCOST	-	Reliability cost, the cost associated with attainment of the current level of reliability, MTBCMA, ($).	*	*
AA	-	Factor which, when multiplied times MCOST, will yield an alternative cost of repair	*	*
BB	-	Factor which, when multiplied times the calculated MTTR, will yield an alternative time of repair associated with cost, AA times MCOST.	*	*
CC	-	Factor which, when multiplied times MCOST, will yield a minimum repair cost regardless of the value of MTTR.	*	*
AS	-	Factor which, when multiplied times SCOST, will yield an alternative cost of supply.	*	*
BS	-	Factor which, when multiplied times the calculated MSRT, will yield an alternative supply response time associated with cost, AS times SCOST.	*	*
CS	-	Factor which, when multiplied times SCOST, will yield a minimum supply cost regardless of the value of MSRT.	*	*
AR	-	Factor which, when multiplied times the calculated value of MTBCMA, yields the maximum possible value of MTBCMA regardless of the investment in reliability.	*	*

NOTES:

1. These values are input in "free" format. All that is required is that there be a space between the values, that they be in the above order, and that the first value be the initial value on its input card.

2. These variables are used only for experimentation with the cost of reliability, maintainability, and supply support as they relate to A_o.

TABLE A-3 Card Type 3, Variable Range Factors

Data Element		Card Columns	Format
FX01(1)	First factor which, when multiplied by the calculated value of MTBCMA, will yield a first alternative value of MTBCMA for parametric analysis	*	*
FX01(2)	Second factor	*	*
⋮			
FX01(N)	Last factor	*	*

NOTES:

1. These values are input in "free" format. All that is required is that there be a space between the values, that they be in the order desired for output, and that the first value be the initial value on its input card.

2. For the subsequent reports the array names are FX02, FX03, FX04 and FX05.

TABLE A-4. Card Type B, Equipment Data

Data Element			Card Columns	Format
Card Type Identifier, "B"			1	A 1
N	-	Equipment identification number assigned by the user	2-4	I 3
RZ	-	Operating time between failures (days)	5-8	I 4
F	-	Equipment operating factor representing the ratio of equipment operating time to elapsed time. (Default value=1.0)	9-11	D(3,2)
Q1	-	Probability of repair at the ship by ship's crew	12-14	D(3,2)
Q2	-	Probability of repair at the ship with technical assistance	15-17	D(3,2)
Q3	-	Probability of repair at a shipyard or tender	18-20	D(3,2)
Q4	-	Probability of repair in overhaul or drydock	21-23	D(3,2)
L1	-	Time to repair at the ship by ship's crew (days)	24-26	I 3
L2	-	Time to repair at the ship with technical assistance (days).	27-29	I 3
L3	-	Time to repair at a shipyard or tender (days)	30-32	I 3
L4	-	Time to repair in overhaul or drydock (days)	33-35	I 3
B1	-	Probability of supply by the ship	36-38	D(3,2)
B2	-	Probability of supply by Mobile Logistic Support Force	39-41	D(3,2)
B3	-	Probability of supply by point of entry, stock point	42-44	D(3,2)
B4	-	Probability of supply by the wholesale system, ICP	45-47	D(3,2)

TABLE A-4 (Continued)

Data Element			Card Columns	Format
T1	-	Time to supply by the ship (days)	48-51	D(4,2)
T2	-	Time to supply by Mobile Logistic Support Force (days)	52-55	D(4,1)
T3	-	Time to supply by point of entry, stock point (days)	56-59	D(4,1)
T4	-	Time to supply by the wholesale system, ICP (days)	60-62	I 3
T5	-	Time to supply by the vendor (days)	63-65	I 3
P	-	Probability that a shipboard repair action requires one or more parts	66-68	D(3,2)
KM	-	Data adjustment factor, maintenance . This is to correct for data inconsistencies which have been identified from processing of maintenance data from different sources. (Default value=1.0)	69-72	D(4,1)
KS	-	Data adjustment factor, supply. (As above but for supply data)	73-76	D(4,1)

IV. OUTPUT REPORTS

The following reports are generated by the program. An example of each is given.

- Equipment Input Data Playback (Figure A-1).
- Report 1: A_o vs. MTBCMA (Figure A-2)
- Report 2: A_o vs. MTTR (Figure A-3)
- Report 3: A_o vs. MSRT (Figure A-4)
- Report 4A: Production Functions; MTBCMA vs. MTTR for Several Values of A_o. (Figure A-5)
- Report 4B: Production Functions; MSRT vs. MTTR for Several Values of A_o (Figure A-6)
- Report 4C: Production Functions; MSRT vs. MTBCMA for Several Values of A_o (Figure A-7)
- Report 5: Ratio of Partial Derivatives (Figure A-8)

```
INPUT DATA FOR EQUIPMENT   7

MEAN TIME BETWEEN CORRECTIVE MAINTENANCF ACTIONS (UNADJUSTED)     90 DAYS

OPERATING FACTOR 1.00     PROBABILITY THAT PARTS ARE REQUIRED      .75

 PROBABILITY OF REPAIR                             TIME TO REPAIR
AT SHIP               .30                 AT SHIP                3.00 DAYS
BY TECH ASSIST        .20                 BY TECH ASSIST         8.00 DAYS
AT YARD OR TENDER     .30                 AT YARD OR TENDER      14   DAYS
IN OVHL OR DRYDOCK    .50                 IN OVHL OR DRYDOCK     45   DAYS

   PROBABILITY OF SUPPLY AVAILABILITY              TIME TO SUPPLY THE SHIP
BY SHIP                                .30  BY SHIP                                .10 DAYS
BY MOBILE LOGISTIC FORCE SHIP (AFS)    .40  BY MOBILE LOGISTIC FORCE SHIP (AFS)   4.0 DAYS
BY POINT OF ENTRY (STOCK POINT)        .30  BY POINT OF ENTRY (STOCK POINT)      24.0 DAYS
BY WHOLESALE SYSTEM (ICP)              .60  BY WHOLESALE SYSTEM (ICP)              60 DAYS
BY VENDOR                             1.00  BY VENDOR                             120 DAYS

DATA ADJUSTMENT FACTOR, MAINTENANCE 1.00
DATA ADJUSTMENT FACTOR, SUPPLY      1.00
```

Figure A-1. Equipment Input Data Playback Report

REPORT 1: ASUBO VS MTBCMA

EQUIPMENT 7

INITIAL VALUES:			
MTBCMA	90.00 DAYS	AVAILABILITY	.77
MTTR	20.71 DAYS		
MSRT	28.87 DAYS		

FACTORS	MTBCMA (DAYS)	ASUBO	DA/DR	-DA/DM	-DA/DS	MTBCMA COST($)
.20	18.00	.398	.01331292	.00880816	.00198184	1923.
.30	27.00	.498	.00925913	.00918910	.00206755	3125.
.40	36.00	.570	.00681001	.00901134	.00202755	4545.
.50	45.00	.623	.00521816	.00863116	.00194201	6250.
.60	54.00	.665	.00412560	.00818880	.00184248	8333.
.70	63.00	.698	.00334343	.00774234	.00174202	10937.
.80	72.00	.726	.00276431	.00731575	.00164604	14286.
.90	81.00	.749	.00232359	.00691806	.00155656	18750.
1.00	90.00	.768	.00198044	.00655156	.00147410	25000.
1.20	108.00	.799	.00148823	.00590790	.00132928	9999999.
1.50	135.00	.832	.00103402	.00513099	.00115447	9999999.
1.75	157.50	.853	.00079744	.00461657	.00103873	9999999.
2.00	180.00	.869	.00063366	.00419246	.00094330	9999999.
2.50	225.00	.892	.00042771	.00353731	.00079589	9999999.
3.00	270.00	.908	.00030800	.00305668	.00068775	9999999.
4.00	360.00	.930	.00018146	.00240115	.00054026	9999999.
5.00	450.00	.943	.00011947	.00197607	.00044461	9999999.
6.00	540.00	.952	.00008456	.00167847	.00037765	9999999.

Figure A-2. Report 1: A_o vs. MTBCMA

REPORT 2: ASUBO VS MTTR

EQUIPMENT 7

INITIAL VALUES:	MTBCMA	90.00 DAYS	AVAILABILITY .77
	MTTR	20.71 DAYS	
	MSRT	28.87 DAYS	

FACTORS	MTTR (DAYS)	ASUBO	DA/DR	-DA/DM	-DA/DS	MTTR COST($)
.20	4.14	.894	.00105033	.00888630	.00199942	9999999.00
.30	6.21	.876	.00120472	.00853154	.00191960	9999999.00
.40	8.28	.859	.00134621	.00819762	.00184446	16799.96
.50	10.35	.842	.00147592	.00788293	.00177366	9599.99
.60	12.43	.826	.00159489	.00758601	.00170685	7799.99
.70	14.50	.811	.00170404	.00730556	.00164375	6981.82
.80	16.57	.796	.00180419	.00704038	.00158408	6514.29
.90	18.64	.782	.00189610	.00678938	.00152761	6211.76
1.00	20.71	.768	.00198044	.00655156	.00147410	6000.00
1.20	24.85	.742	.00212884	.00611194	.00137519	5723.07
1.50	31.06	.706	.00230834	.00553106	.00124449	5485.71
1.75	36.24	.678	.00242563	.00510800	.00114930	5364.70
2.00	41.42	.653	.00251913	.00473167	.00106463	5280.00
2.50	51.77	.607	.00265057	.00409385	.00092112	5169.23
3.00	62.13	.567	.00272734	.00357681	.00080478	5100.00
4.00	82.84	.502	.00277774	.00279839	.00062964	5018.18
5.00	103.55	.450	.00274989	.00224897	.00050602	4971.43
6.00	124.26	.408	.00268310	.00184679	.00041553	4941.18

Figure A-3. Report 2: A_o vs. MTTR

REPORT 3: ASUBO VS MSRT

EQUIPMENT 7

INITIAL VALUES: MTBCMA 90.00 DAYS AVAILABILITY .77
MTTR 20.71 DAYS
MSRT 28.87 DAYS

FACTORS	MSRT (DAYS)	ASUBO	DA/DR	-DA/DM	-DA/DS	MSRT COST($)
.20	5.77	.804	.00175427	.00717357	.00161405	9999999.00
.30	8.66	.799	.00178528	.00709109	.00159549	9999999.00
.40	11.55	.794	.00181546	.00701002	.00157725	11999.99
.50	14.43	.790	.00184484	.00693033	.00155932	6857.13
.60	17.32	.785	.00187344	.00685199	.00154170	5454.54
.70	20.21	.781	.00190128	.00677498	.00152437	4800.00
.80	23.10	.776	.00192839	.00669925	.00150733	4421.05
.90	25.98	.772	.00195477	.00662479	.00149058	4173.91
1.00	28.87	.768	.00198044	.00655156	.00147410	4000.00
1.20	34.64	.759	.00202977	.00640870	.00144196	3771.43
1.50	43.30	.747	.00209894	.00620301	.00139568	3574.47
1.75	50.52	.737	.00215243	.00603908	.00135879	3473.68
2.00	57.74	.728	.00220242	.00588156	.00132335	3402.98
2.50	72.17	.709	.00229269	.00558446	.00125650	3310.34
3.00	86.61	.691	.00237133	.00530932	.00119460	3252.34
4.00	115.48	.658	.00249896	.00481670	.00108376	3183.67
5.00	144.35	.629	.00259419	.00438960	.00098766	3144.38
6.00	173.22	.601	.00266384	.00401688	.00090380	3118.94

Figure A-4. Report 3: A_o vs. MSRT

REPORT 4A: MTBCMA VS MTTR FOR SEVERAL VALUES OF ASUBO

EQUIPMENT 7

INITIAL VALUES: MTBCMA 90.00 DAYS AVAILABILITY .77
MTTR 20.71 DAYS
MSRT 28.87 DAYS

FACTORS	MTTR (DAYS)	MTBCMA(DAYS) FOR GIVEN VALUES OF ASUBO .25	.40	.50	.70	.75	.80	.85	.90	.95	.99
.20	4.14	4	7	11	25	32	43	60	96	202	1053
.30	6.21	4	8	13	30	38	51	72	114	241	1258
.40	8.28	5	10	15	34	44	59	84	133	281	1463
.50	10.35	6	11	17	39	51	67	95	152	320	1668
.60	12.43	6	13	19	44	57	76	107	170	360	1873
.70	14.50	7	14	21	49	63	84	119	189	399	2078
.80	16.57	8	15	23	54	69	92	131	208	438	2283
.90	18.64	8	17	25	59	75	101	142	226	478	2488
1.00	20.71	9	18	27	63	82	109	154	245	517	2693
1.20	24.85	10	21	31	73	94	125	178	282	596	3103
1.50	31.06	13	25	38	88	113	150	213	338	714	3718
1.75	36.24	14	28	43	100	128	171	242	385	812	4231
2.00	41.42	16	32	48	112	144	192	272	431	910	4744
2.50	51.77	19	39	58	136	175	233	330	524	1107	5769
3.00	62.13	23	46	69	160	206	275	389	618	1304	6794
4.00	82.84	30	60	89	208	268	357	506	804	1697	8844
5.00	103.55	37	73	110	257	330	440	624	990	2091	10894
6.00	124.26	44	87	131	305	392	523	741	1177	2484	12945

Figure A-5. Report 4A: MTBCMA vs. MTTR for Several Values of A_o

REPORT 4B: MSRT VS MTTR FOR SEVERAL VALUES OF ASUBO

EQUIPMENT 8

INITIAL VALUES: MTBCMA 90.00 DAYS AVAILABILITY .72
MTTR 31.35 DAYS
MSRT 52.50 DAYS

	MTTR	MSRT(DAYS) FOR GIVEN VALUES OF ASUBO									
FACTORS	(DAYS)	.25	.40	.50	.70	.75	.80	.85	.90	.95	.99
.20	6.27	3516	1716	1116	431	316	216	128	50	-20	-71
.30	9.40	3475	1675	1075	384	275	175	86	8	-62	-113
.40	12.54	3433	1633	1033	347	233	133	45	-34	-104	-155
.50	15.67	3391	1591	991	305	191	91	3	-76	-146	-197
.60	18.81	3349	1549	949	263	149	49	-39	-117	-188	-239
.70	21.94	3307	1507	907	222	107	7	-81	-159	-229	-280
.80	25.08	3266	1466	866	180	66	-34	-123	-201	-271	-322
.90	28.21	3224	1424	824	138	24	-76	-164	-243	-313	-364
1.00	31.35	3182	1382	782	96	-18	-118	-206	-285	-355	-406
1.20	37.62	3098	1298	698	13	-102	-202	-290	-368	-438	-489
1.50	47.02	2973	1173	573	-113	-227	-327	-415	-494	-564	-615
1.75	54.86	2869	1069	469	-217	-331	-431	-520	-598	-668	-719
2.00	62.70	2764	964	364	-322	-436	-536	-624	-703	-773	-824
2.50	78.37	2555	755	155	-531	-645	-745	-833	-912	-982	-1033
3.00	94.05	2346	546	-54	-740	-854	-954	-1042	-1121	-1191	-1242
4.00	125.40	1928	128	-472	-1158	-1272	-1372	-1460	-1539	-1609	-1660
5.00	156.75	1510	-290	-890	-1576	-1690	-1790	-1878	-1957	-2027	-2078
6.00	188.10	1092	-708	-1308	-1994	-2108	-2208	-2296	-2375	-2445	-2496

Figure A-6. Report 4B: MSRT vs. MTTR for Several Values of A_o

REPORT 4C: MTBCMA VS MSRT FOR SEVERAL VALUES OF ASUBO

EQUIPMENT 8

INITIAL VALUES: MTBCMA 90.00 DAYS AVAILABILITY .72
MTTR 31.35 DAYS
MSRT 52.50 DAYS

FACTORS	MSRT (DAYS)	MTBCMA(DAYS) FOR GIVEN VALUES OF ASUBO .25	.40	.50	.70	.75	.80	.85	.90	.95	.99
.20	10.50	11	21	32	75	96	129	182	289	611	3182
.30	15.75	11	22	33	76	98	130	184	293	618	3221
.40	21.00	11	22	33	77	99	132	187	296	626	3260
.50	26.25	11	22	33	78	100	133	189	300	633	3299
.60	31.50	11	22	34	79	101	135	191	303	641	3338
.70	36.75	11	23	34	80	102	136	193	307	648	3376
.80	42.00	11	23	34	80	103	138	195	310	655	3415
.90	47.25	12	23	35	81	105	140	198	314	663	3454
1.00	52.50	12	24	35	82	106	141	200	318	670	3493
1.20	63.00	12	24	36	84	108	144	204	325	685	3571
1.50	78.75	12	25	37	87	112	149	211	335	708	3688
1.75	91.87	13	25	38	89	115	153	217	344	727	3786
2.00	105.00	13	26	39	92	118	157	222	353	745	3883
2.50	131.24	14	27	41	96	124	165	233	371	783	4078
3.00	157.49	14	29	43	101	129	173	245	388	820	4273
4.00	209.99	16	31	47	110	141	188	267	424	895	4663
5.00	262.49	17	34	51	119	153	204	289	459	970	5053
6.00	314.99	18	37	55	128	165	220	312	495	1045	5442

Figure A-7. Report 4C: MTBCMA vs. MSRT for Several Values of A_o

REPORT 5: RATIO OF PARTIAL DERIVATIVES

EQUIPMENT B

INITIAL VALUES: MTBCMA 90.00 DAYS AVAILABILITY .72
MTTR 31.35 DAYS
MSRT 52.50 DAYS

ASUBO	RATIO -DA/DR/ DA/DS	MSRT (DAYS)	RATIO -DA/DR / DA/DM	MTTR (DAYS)
.20	53.333282	4382.00	3.999997	356.06
.30	31.111099	2332.00	2.333333	206.06
.40	19.999985	1332.00	1.499999	131.06
.50	13.333323	782.00	1.000000	86.06
.60	8.888881	352.00	.666666	56.06
.70	5.714285	95.27	.428571	34.63
.75	4.444445	-16.00	.333333	26.06
.80	3.333334	-118.00	.250000	18.56
.85	2.352950	-200.23	.176471	11.95
.90	1.481483	-264.67	.111111	6.06
.92	1.159419	-313.65	.086956	3.89
.94	.851072	-341.40	.063830	1.81
.95	.701762	-354.64	.052631	.80
.96	.555551	-358.00	.041667	-.19
.97	.412375	-380.69	.030928	-1.15
.98	.272113	-393.51	.020408	-2.10
.99	.134682	-407.68	.010101	-3.03

Figure A-8. Report 5: Ratio of Partial Derivatives

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APPENDIX B

MATHEMATICAL DESCRIPTION
of the
OPTIMAL A_o COSAL MODEL

APPENDIX B: MATHEMATICAL DESCRIPTION OF THE A_o COSAL MODEL

CONTENTS

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I. INTRODUCTION

In this appendix, the optimal A_o COSAL model is described in mathematical terms. First, the basic assumptions of the model are established. The model is then formulated in terms of its structure and objective function. Finally, the solution procedure is given.

II. ASSUMPTIONS

Items are assumed to be interrelated in an (arborescence) hierarchy structure. The item at the top of the structure is referred to as the "equipment." Subordinate parts are referred to as "items." Levels of the hierarchy are referred to as "indenture" levels and are assumed to be numbered sequentially starting from the top. No limit is placed on the number of indenture levels or the number of equipments except as may be imposed by computer storage capacity.

A two-echelon supply system is assumed, consisting of one or more "users" at the first (lowest) echelon and one "system" activity at the second (highest) echelon. Users obtain resupply (if available) from system stock. The system obtains resupply from a manufacturer which can always deliver after a given procurement lead time. Lateral resupply (user to user) is not permitted. System stocks may be physically distributed, but it is assumed that the user resupply time is the same regardless of system stock location.

Three levels of maintenance are assumed, organizational which is collocated with user stocks, IMA and depot. Items repaired at organizational level are returned to the collocated stocks for reuse. Items repaired at IMA and depot level are returned to system stock for reuse. Total repair cycles (time from first identification as a reparable to time returned to serviceable stock) may differ by maintenance level but not by location within maintenance level.

The demand process is assumed to be represented by members of the compound Poisson family. Demand is assumed stationary with dynamic changes being considered by periodic recalculation of levels.

III. MODEL FORMULATION

Consider an arbitrary item i of equipment e (which may be e itself). Let $u = 1, 2, \ldots, U$ represent the user sites. Let $u = 0$ represent the system. In the equations below, u is assumed to range from 0 to U unless otherwise noted. The optimal A_o COSAL model is then defined by equations (1) - (5).

(1) $$D_{iu}(S,\theta) = \frac{\sum_{x > S_{iu}} (x - S_{iu}) p(x, \theta_{iu})}{M_{iu}}$$

where

D_{iu} = expected delay per demand upon inventory for item i at location u

S_{iu} = stock level of item i at location u

M_{iu} = expected number of demands upon inventory per unit for item i at location u

$p(x, \theta_{iu})$ = probability of x units of stock reduction for item i at location u with mean rate of reduction given by θ_{iu}

(2) $$\theta_{iu} = M_{iu} \{\gamma_{iu}(L_{iu} + \bar{L}_{iu}) + (1 - \gamma_{iu})(R_{iu} + \bar{R}_{iu})\}$$

where

L_{iu} = average resupply lead time assuming stock availability at the resupply source

$\bar{L}_{iu}$ = additional lead time due to expected stock shortages at the resupply source

R_{iu} = average repair cycle assuming availability of repair parts at the next lower indenture level

$\bar{R}_{iu}$ = additional repair cycle due to expected shortages of repair parts

γ_{iu} = expected inventory losses (scrap + BCM) as a fraction of M_{iu}

(3) $$\bar{L}_{iu} = D_{i0} \quad (u = 1, 2, \ldots, U)$$

$$\bar{L}_{i0} = 0$$

(4) $$\bar{R}_{iu} = \frac{\sum_{j \in i} M_{ju} D_{ju}}{\sum_{j \in i} M_{ju}}$$ where j identifies parts within i at the next lower indenture level

$$\bar{R}_{iu} = 0$$ if i has no subordinate parts

(5) $$A_{eu} = 1 - M_{eu} D_{eu}$$

where

A_{eu} = fraction of time equipment e is available for use location u (u = 1, 2, k, . . . , U)

In equation (1), the summation term gives the expected number of back orders for a stock level of S_{iu} which is equivalent to the expected length of time the stock is in a back order status. Dividing by the expected number of demands gives the expected delay in satisfying a demand.

The second equation gives the effective mean reduction in stock. The first term (involving resupply lead time) represents losses from stock due to scrap or BCMs to other locations. The second term represents losses due to amounts cycling through local repair. The parameters M_{iu} and γ_{iu} are calculated by the Material Flow model described in Appendix C.

Equation (3) establishes the connection between supply echelons. It states that the additional delay in obtaining resupply of a user's stock is equal to the expected delay per demand upon system stocks.

Equation (4) establishes the connection between indenture levels of the parts hierarchy. It states that the additional delay in repairing an assembly is equal to the weighted average of expected delays per demand upon stocks of items at the next lower indenture level.

Equation (5) gives the operational availability of the equipment in terms of factors defined by previous equations. This definition of A_o conforms to the one given and discussed in Section V of the report.

IV. OBJECTIVE FUNCTION

Having defined the structure of the model, the objective function can be stated as follows:

Find values for S_{ku} for all items $k \epsilon e$ and all locations u which minimize D_{eu} ($u = 1, 2, \ldots, U$) subject to

$$\sum_k c_k S_{ku} = B_u$$

where

c_k = unit cost of item k

B_u = given budget for spares at user u

It should be noted, by referring to equation (5), that minimizing D_{eu} is equivalent to maximizing A_{eu}, the operational availability of equipment e.

If the equipment e is not subject to stockage, as was assumed in the two case studies, then S_{eu} in equation (1) and γ_{eu} in equation (2) are set to zero. In this case,

$$D_{eu} = \frac{\theta_{eu}}{M_{eu}} = R_{eu} + \bar{R}_{eu}$$

Using equation (4), the objective function in this case can be rewritten as follows:

Find S_{ku} ($k \epsilon e$, $k \neq e$) which minimizes $\sum_{i \epsilon e} M_{iu} D_{iu}$ (i at the next lower indenture level) subject to

$$\sum_k c_k S_{ku} = B_u$$

V. SOLUTION PROCEDURE

The optimal solution to the problem defined above is found by a recursive procedure based upon equations (1) - (5). Suppose that particular values are assigned to stock levels, S_{ku}, for all u and all items $k \varepsilon e$. Then define

$$D(S_{iu}, \bar{L}_{iu}, \bar{R}_{iu}) \quad = \quad D_{iu}(S, \theta)$$

for any item $i \varepsilon e$, where $\bar{L}$ and $\bar{R}$ are the attained expected delays for lack of system stock or repair parts, respectively, associated with the given stock levels, S_{ku}. Define

$$\text{(a)} \quad \Delta_S D_{iu} = D(S_{iu}, \bar{L}_{iu}, \bar{R}_{iu}) - D(S_{iu}+1, \bar{L}_{iu}, \bar{R}_{iu})$$

$$\text{(6)} \quad \text{(b)} \quad \Delta_L D_{iu} = D(S_{iu}, \bar{L}_{iu}, \bar{R}_{iu}) - D(S_{iu}, \bar{L}^*_{iu}, \bar{R}_{iu})$$

$$\text{(c)} \quad \Delta_R D_{iu} = D(S_{iu}, \bar{L}_{iu}, \bar{R}_{iu}) - D(S_{iu}, \bar{L}_{iu}, \bar{R}^*_{iu})$$

where

$\bar{L}^*_{iu}$ = least value of $\bar{L}_{iu}$ obtainable by a unit increase in stock of some part $\omega \varepsilon i$ at the supply source for u

$\bar{R}^*_{iu}$ = least value of $\bar{L}_{iu}$ obtainable by a unit increase in stock of some part $r \varepsilon i$ at u

Letting ω^* represent the part which satisfies $\bar{L}^*_{iu}$ and r^* the part which satisfies $\bar{R}^*_{iu}$, find the largest of

$$\text{(7)} \qquad \text{(a)} \quad \frac{\Delta_S D_{iu}}{c_i} \qquad \text{(b)} \quad \frac{\Delta_L D_{iu}}{c_{\omega^*}} \qquad \text{(c)} \quad \frac{\Delta_R D_{iu}}{c_{r^*}}$$

and let

$$\text{(a)} \quad D^*_{iu} = D(S_{iu}+1, \bar{L}_{iu}, \bar{R}_{iu})$$

$$\text{(8)} \quad \text{(b)} \quad = D(S_{iu}, \bar{L}^*_{iu}, \bar{R}_{iu})$$

$$\text{(c)} \quad = D(S_{iu}, \bar{L}_{iu}, \bar{R}^*_{iu})$$

according to which of (a), (b) or (c) in equation (7) is largest, respectively.

With the above definitions and using equations (3) and (4), a recursion across supply echelons and through the parts hierarchy is given by:

$$(9) \qquad \bar{L}^*_{iu} = D^*_{io}$$

$$(10) \qquad \bar{R}^*_{iu} = \frac{\sum\limits_{j \in i-j'} M_{ju} D_{ju} + M_{j'u} D^*_{j'u}}{\sum\limits_{j \in i} M_{ju}}$$

where j identifies parts within i at the next lower indenture and j' = r* or contains r* as a lower level part.

The above solution procedure is designed to find the particular item in e (inclusive) and stockage location u such that a one-unit increase in the stock level (given existing stocks, S_{ku}) will yield the largest decrease in $\dot{D}_{eu}$ per dollar. The recursion commences with system stock for the lowest indentured items. In this case, 6(b) and 6(c) are zero and D* for the item at all user sites using (9) and values of $\bar{R}^*$ for the next higher assemblies at the system level using (10). Next, equations (7) and (8) are applied to lowest level parts at user sites and to next-to-lowest indentured items at the system level, since all required factors are known. The procedure continues up the parts hierarchy structure at the system level, with each step yielding values for $\bar{L}^*$ at the user sites and $\bar{R}^*$ for next higher assemblies at the system level. At the same time, the recursion continues up the parts hierarchy at user sites yielding values of $\bar{R}^*$ for the next higher assemblies. The procedure terminates at the highest indenture level yielding the largest per dollar reduction in expected delay per equipment failure obtainable by a one-unit increase of stock of some subordinate part.

Having found the item and location which yields the "best" per unit increase in A_o, the stock level for the item and location is increased by one unit and the procedure is repeated. This process continues until the specified budget goals are satisfied.

The four kinds of optimization defined in Section V of the report are accomplished by specifying starting stock levels and/or by slight modifications of the solution procedure. For the pure optimization case, stock levels for all items at all sites are set to zero at the start. For the constrained case, stock levels at some locations are set to specified values and are not allowed to change in the optimizing procedure. For the enhanced case, initial stock levels are specified at some or all sites and are

permitted to increase in the solution procedure. For the budget reclama case, the solution algorithm is slightly changed to consider stock reductions instead of increases; also, the least of the (absolute) values given in (7) is sought instead of the largest.

APPENDIX C

TECHNICAL DESCRIPTION
of the
MATERIAL FLOW MODEL

The Material Flow model is designed to calculate rates of flow of material at and among locations in the overall logistics support system. The calculations are made based upon failure data, operating factors, site interrelations, LOR codings, and item parameters given by input data. Outputs of the model are used by the optimal A_o COSAL model to determine shipboard stockage requirements. A technical description of the model is given in this Appendix, together with an example of its operation.

As a preliminary or setup operation, two factors are calculated for use in determining effective numbers of failures per unit time (quarter). The first factor, defined as "Equipment Operating Unit-Months," is calculated for each end-equipment E, location L, and quarter Q according to the following formula:

$$\begin{pmatrix}\text{Equipment}\\ \text{Operating}\\ \text{Unit-Months}\end{pmatrix}_{E,L,Q} = \begin{pmatrix}\text{\# of units of}\\ \text{Equipment E}\\ \text{at Location L}\end{pmatrix}_{E,L} \begin{pmatrix}\text{\# of months}\\ \text{installed at L}\\ \text{in Quarter Q}\end{pmatrix}_{E,L,Q} \begin{pmatrix}\text{Location}\\ \text{Operating}\\ \text{Factor}\end{pmatrix}_{E,L}$$

In this formula, the number of units of equipment E positioned at location L is given by the delivery schedule. The number of months the equipment is installed at L during quarter Q will be 3 if the equipment was delivered prior to the quarter. If delivered during the quarter, the number will be 0.5, 1.5 or 2.5 according to the month of delivery within the quarter (delivery is assumed to occur halfway through the month). The location operating factor for the equipment at location L is given by input data as the fraction of time the equipment actually operates at the location after delivery.

The second factor, defined as the "Item Operating Unit-Months," is calculated for each item I and end-equipment E according to the following recursive procedure:

$$\begin{pmatrix}\text{Item Operating}\\ \text{Unit-Months}\end{pmatrix}_{E,I} = \sum_A \begin{pmatrix}\text{Item Oper.}\\ \text{Unit-Months}\end{pmatrix}_{E,I,A}$$

where

$$\begin{pmatrix}\text{Item Oper.}\\ \text{Unit-Months}\end{pmatrix}_{I_{j+1},I,A} = \begin{pmatrix}\text{\# units of}\\ I_j \text{ in } I_{j+1}\end{pmatrix} \begin{pmatrix}\text{Fraction of time}\\ I_j \text{ operates}\\ \text{when } I_{j+1} \text{ operates}\end{pmatrix} \begin{pmatrix}\text{Item Oper.}\\ \text{Unit-Months}\end{pmatrix}_{I_j,I,A}$$

and j = 1, 2, . . . until I_{j+1} = E, the end-equipment. The summation is over all appearances, A, of item I in end-equipment E. The recursion is initiated by setting

$$I_1 = \text{given item, } I$$

$$\begin{pmatrix} \text{Item Oper.} \\ \text{Unit-Months} \end{pmatrix}_{I_1,I,A} = 1$$

The result, Item Operating Unit-Months, gives the number of operational unit-months of item I per operational month of end-equipment E over all appearances of I in E. This factor, when multiplied against the Equipment Operating Unit-Months and summed over end-equipments, determines the amount of usage of the item over time upon which expected failures are based. The two factors are separately calculated and stored to conserve storage space; they are multiplied and summed as needed in the subsequent calculations.

Next, the various rates defined in Section II of the report are calculated by a recursive procedure using the general formulas given below. In these formulas, subscripts, I, L, Q, and E refer, respectively, to a particular item, location, quarter, and end-equipment. The superscript, R, refers to "real" and detected false removals while U refers to undetected false removals. Values for BCM and scrap rates used in the formulas are assigned according to LOR designations and values given by input data for various maintenance levels. It should be noted that the computation is recursive according to the parts hierarchy since the first equation uses the factor, "Amount Repaired," for assembly A (the next higher assembly for item I) which is given by equation 13 when the formulas are applied to A.

1. $$\begin{pmatrix} \text{Local} \\ \text{Generations} \end{pmatrix}_{I,L,Q} = \begin{pmatrix} \text{Failure} \\ \text{Rate} \end{pmatrix}_{I,L,Q} \quad \text{if I = end-equipment,}$$

$$= \frac{\begin{pmatrix} \text{Amount} \\ \text{Repaired} \end{pmatrix}_{A,L,Q} \begin{pmatrix} \text{Failure} \\ \text{Rate} \end{pmatrix}_{I,OS,Q}}{\begin{pmatrix} \text{Failure} \\ \text{Rate} \end{pmatrix}_{A,OS,Q}}$$

if I has a next higher assembly, A. Subscript OS refers to the operating site at which the failures originally occur. The Amount Repaired factor is given by formula 13 below. The Failure Rate factor is given by:

$$\begin{pmatrix}\text{Failure}\\ \text{Rate}\end{pmatrix}_{I,L,Q} = \frac{730.5}{(\text{MTBF})_I} \sum_E \begin{pmatrix}\text{Equip. Oper}\\ \text{Unit-Months}\end{pmatrix}_{E,L,Q} \begin{pmatrix}\text{Item Oper.}\\ \text{Unit Months}\end{pmatrix}_{E,I}$$

2. $$\begin{pmatrix}\text{False}\\ \text{Removals}\end{pmatrix}_{I,L,Q} = \begin{pmatrix}\text{Local}\\ \text{Generations}\end{pmatrix}_{I,L,Q} \begin{pmatrix}\text{False Removal}\\ \text{Rate}\end{pmatrix}_{I,L}$$

3. $$\begin{pmatrix}\text{Total}\\ \text{Removals}\end{pmatrix}_{I,L,Q} = \begin{pmatrix}\text{Local}\\ \text{Generations}\end{pmatrix}_{I,L,Q,} + \begin{pmatrix}\text{False}\\ \text{Removals}\end{pmatrix}_{I,L,Q}$$

4. $$\begin{pmatrix}\text{Detected}\\ \text{False Rem.}\end{pmatrix}_{I,L,Q} = \begin{pmatrix}\text{False}\\ \text{Removals}\end{pmatrix}_{I,L,Q} \begin{pmatrix}\text{False Removal}\\ \text{Detection Rate}\end{pmatrix}_{I,L}$$

5. $$\begin{pmatrix}\text{Net}\\ \text{Removals}\end{pmatrix}^{R}_{I,L,Q} = \begin{pmatrix}\text{Local}\\ \text{Generations}\end{pmatrix}_{I,L,Q} + \begin{pmatrix}\text{False}\\ \text{Removals}\end{pmatrix}_{I,L,Q} - \begin{pmatrix}\text{Detected}\\ \text{False Removals}\end{pmatrix}_{I,L,Q}$$

6. $$\begin{pmatrix}\text{BCM}\\ \text{Receipts}\end{pmatrix}^{R,U}_{I,L,Q} = \sum_{LL} (\text{BCMs})^{R,U}_{I,LL,Q}$$

where the summation is over all lower level sites, LL, forwarding BCM amounts to L, including real failures (R) and undetected false removals (U).

7. $$\begin{pmatrix}\text{Total Rep.}\\ \text{Inductions}\end{pmatrix}^{R,U}_{I,L,Q} = \begin{pmatrix}\text{Net}\\ \text{Removals}\end{pmatrix}^{R,U}_{I,L,Q} + \begin{pmatrix}\text{BCM}\\ \text{Receipts}\end{pmatrix}^{R,U}_{I,L,Q}$$

8. $$\begin{pmatrix}\text{Total}\\ \text{BCMs}\end{pmatrix}^{R,U}_{I,L,Q} = \begin{pmatrix}\text{Total Rep.}\\ \text{Inductions}\end{pmatrix}^{R,U}_{I,L,Q} (\text{BCM Rate})_{I,L}$$

9. $$\begin{pmatrix}\text{BCMs}\\ \text{IMA}\end{pmatrix}^{R,U}_{I,L,Q} = \begin{pmatrix}\text{Total}\\ \text{BCMs}\end{pmatrix}^{R,U}_{I,L,Q} (\text{IMA-Depot Split})_{I,L}$$

10. $\begin{pmatrix}\text{BMCs}\\\text{Depot}\end{pmatrix}^{R,U}_{I,L,Q} = \begin{pmatrix}\text{Total}\\\text{BCMs}\end{pmatrix}^{R,U}_{I,L,Q} - \begin{pmatrix}\text{BCMs}\\\text{IMA}\end{pmatrix}^{R,U}_{I,L,Q}$

11. $\begin{pmatrix}\text{Local}\\\text{Repairs}\end{pmatrix}_{I,L,Q} = \begin{pmatrix}\text{Total Rep.}\\\text{Inductions}\end{pmatrix}^{R}_{I,L,Q} - \begin{pmatrix}\text{Total}\\\text{BCMs}\end{pmatrix}^{R}_{I,L,Q}$

12. $\begin{pmatrix}\text{Scrap}\\\text{Losses}\end{pmatrix}_{I,L,Q} = \begin{pmatrix}\text{Local}\\\text{Repairs}\end{pmatrix}_{I,L,Q} (\text{Scrap Rate})_{I,L}$

13. $\begin{pmatrix}\text{Amount}\\\text{Repaired}\end{pmatrix}_{I,L,Q} = \begin{pmatrix}\text{Local}\\\text{Repairs}\end{pmatrix}_{I,L,Q} - \begin{pmatrix}\text{Scrap}\\\text{Losses}\end{pmatrix}_{I,L,Q}$

14. $\begin{pmatrix}\text{Amount}\\\text{Verified}\end{pmatrix}_{I,L,Q} = \begin{pmatrix}\text{Total}\\\text{Removals}\end{pmatrix}_{I,L,Q} + \begin{pmatrix}\text{BCM}\\\text{Receipts}\end{pmatrix}^{R}_{I,L,Q} + \begin{pmatrix}\text{BCM}\\\text{Receipts}\end{pmatrix}^{U}_{I,L,Q}$

To illustrate the use of these formulas in determining the various rates, an equipment with 3 indenture levels but with only 1 part at each level may be considered. The 3 items are identified as a component (at the first indenture), an assembly (at the second indenture) and a part (at the third indenture). Repair is assumed to occur at organizational level for all 3 items, with amounts beyond repair capability being sent to intermediate and depot repair facilities. Three user sites are assumed, supported by 1 IMA and 1 depot. Only one type of end-equipment is assumed and since the computation is similar for each quarter, only one quarter of the program is considered. Data assumptions for the example are as follows:

			Scrap Rate			BCM Rate		False Removal Rate			False Removal Detected Rate		
	MTBF	Oper. Fact.	ORG	IMA	DEP	ORG	IMA	ORG	IMA	DEP	ORG	IMA	DEP
Component	100	.8	.05	.02	.01	.20	.20	.10	.05	.02	.50	.50	.50
Assembly	200	.6	.10	.05	.02	.10	.10	.20	.10	.05	.50	.50	.50
Part	400	.5	.20	.10	.05	.05	.05	.30	.20	.10	.50	.50	.50

	BCM IMA-Depot Split	Equip. Oper. Unit-Months
Site 1	.9	10
Site 2	.9	20
Site 3	.9	30

With these factors, the full computation for all 3 items and all 5 operating and support sites is shown below in Figure C-1. The computation is done first for the component, then for the assembly, and finally for the part. For each item, the computation pattern is the same. First, operational sites are considered, then the IMA, and finally the depot. For each site, two columns of data are provided. According to the context, the column labeled "R" represents real and detected false removals whereas the column labeled "U" represents undetected false removals. The distinction is made because undetected false removals are assumed to be subject to BCM actions whereas detected ones are not. All false removals, detected or not, are assumed to undergo verify operations but not repair tasks.

COMPONENT	SITE 1 R	SITE 1 U	SITE 2 R	SITE 2 U	SITE 3 R	SITE 3 U	IMA R	IMA U	DEPOT R	DEPOT U
1. Local Generations	58.44		116.88		175.32					
2. False Removals	5.84		11.69		17.53					
3. Total Removals	64.28		128.57		192.85					
4. Detect. False Removals	2.92		5.84		8.76					
5. Net Removals	58.44	2.92	116.88	5.85	175.32	8.77				
6. BCM Receipts							63.11	3.13	19.64	.98
7. Total Rep. Inductions	58.44	2.92	116.88	5.85	175.32	8.77	63.11	3.13	19.64	.98
8. BCM's, Total	11.69	.56	23.38	1.17	35.06	1.75	12.62	.63		
9. BCM's, IMA	10.52	.50	21.04	1.05	31.55	1.58				
10. BCM's, Depot	1.17	.06	2.34	.12	3.51	.17	12.62	.63		
11. Local Repairs	46.75		93.50		140.26		50.49		19.64	
12. Scrap Losses	2.34		4.68		7.01		1.01		.20	
13. Amount Repaired	44.41		88.82		133.25		49.48		19.44	
14. Amount Verified	64.28		128.57		192.85		66.24		20.62	
ASSEMBLY										
1. Local Generations	16.65		33.31		49.97		18.56		7.29	
2. False Removals	3.33		6.66		9.99		1.86		.36	
3. Total Removals	19.98		39.97		59.96		20.42		7.65	
4. Detect. False Removals	1.66		3.33		4.99		.93		.18	
5. Net Removals	16.65	1.67	33.31	3.33	49.97	5.00	18.56	.93	7.29	.18
6. BCM Receipts							9.00	.90	3.76	.28
7. Total Rep. Inductions	16.65	1.67	33.31	3.33	49.97	5.00	27.56	1.83	11.05	.46
8. BCM's, Total	1.67	.17	3.33	.33	5.00	.50	2.76	.18		
9. BCM's, IMA	1.50	.15	3.00	.30	4.50	.45				
10. BCM's, Depot	.17	.02	.33	.03	.50	.05	2.76	.18		
11. Local Repairs	14.98		29.98		44.97		24.80		11.05	
12. Scrap Losses	1.50		3.00		4.50		1.24		.22	
13. Amount Repaired	13.48		26.98		40.47		23.56		10.83	
14. Amount Verified	19.98		39.97		59.96		30.32		11.69	
PART										
1. Local Generations	5.62		11.24		16.86		9.82		4.51	
2. False Removals	1.69		3.37		5.06		1.96		.45	
3. Total Removals	7.31		14.61		21.92		11.78		4.96	
4. Detect. False Removals	.84		1.63		2.53		.98		.22	
5. Net Removals	5.62	.85	11.24	1.64	16.86	2.53	9.82	.98	4.51	.23
6. BCM Receipts							1.51	.23	.74	.08
7. Total Rep. Inductions	5.62	.85	11.24	1.64	16.86	2.53	11.33	1.21	5.25	.31
8. BCM's, Total	.28	.04	.56	.08	.84	.13	.57	.06		
9. BCM's, IMA	.25	.04	.50	.07	.76	.12				
10. BCM's, Depot	.03		.06	.01	.08	.01	.57	.06		
11. Local Repairs	5.34		10.68		16.02		10.76		5.25	
12. Scrap Losses	1.07		2.14		3.20		1.08		.26	
13. Amount Repaired	4.27		8.54		12.82		9.68		4.99	
14. Amount Verified	7.31		14.61		21.92		13.52		5.78	

Figure C-1. Example Calculation of Repair and Verify Rates